



Calhoun: The NPS Institutional Archive
DSpace Repository

Theses and Dissertations

1. Thesis and Dissertation Collection, all items

1965

An experimental investigation of the effects of
position and motion on the frequency stability
of certain crystal oscillators

Austin, Donald R.

Monterey, California: U.S. Naval Postgraduate School

<http://hdl.handle.net/10945/12158>

This publication is a work of the U.S. Government as defined in Title 17, United States Code, Section 101. Copyright protection is not available for this work in the United States.

Downloaded from NPS Archive: Calhoun



Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943

<http://www.nps.edu/library>

NPS ARCHIVE

1965

AUSTIN, D.

AN EXPERIMENTAL INVESTIGATION OF THE
EFFECTS OF POSITION AND MOTION ON
THE FREQUENCY STABILITY OF CERTAIN
CRYSTAL OSCILLATORS

DONALD R. AUSTIN

**DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CA 93943-6101**

AN EXPERIMENTAL INVESTIGATION OF THE EFFECTS
OF POSITION AND MOTION ON THE FREQUENCY
STABILITY OF CERTAIN CRYSTAL OSCILLATORS

* * * * *

Donald R. Austin

AN EXPERIMENTAL INVESTIGATION OF THE EFFECTS
OF POSITION AND MOTION ON THE FREQUENCY
STABILITY OF CERTAIN CRYSTAL OSCILLATORS

by

Donald R. Austin

//
Lieutenant, Civil Engineer Corps, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

United States Naval Postgraduate School
Monterey, California

1 9 6 5

Thesis
A 165
C-7

NPS ARCHIVE
K165
AUSTIN, D.

AN EXPERIMENTAL INVESTIGATION OF THE EFFECTS
OF POSITION AND MOTION ON THE FREQUENCY
STABILITY OF CERTAIN CRYSTAL OSCILLATORS

by

Donald R. Austin

This work is accepted as fulfilling
the thesis requirements for the degree of
MASTER OF SCIENCE

IN

ENGINEERING ELECTRONICS

from the

United States Naval Postgraduate School

ABSTRACT

Crystal oscillators are now available with frequency stabilities of a few parts in 10^{10} or 10^{11} . One application of such stability is in navigation systems, where geographic position may be determined by phase-comparing a received frequency-stable signal with a local frequency-stable signal. Errors may be introduced, however, by the effects of static position and of motion on the frequency stability of the oscillators employed. A testing program including static position, swinging motion, vibration, and shock tests was devised to determine the extent of such effects. The program is described and the results are presented in both tabular and graphic form.

TABLE OF CONTENTS

Section	Title	Page
1.	Introduction	1
2.	Oscillators Tested	2
3.	Test Program	4
	Purpose and Procedure	4
	Circuits and Equipment	5
	Description of Tests	9
	Environment	12
4.	Data Acquisition and Processing	13
	Acquisition	13
	Processing	14
5.	Test Results	21
6.	Observations	54
7.	Recommendations for Further Study	59
8.	Bibliography	60
9.	Appendix	61

LIST OF TABLES

Table		Page
I.	Static Test Descriptions	9
II.	Swing Test Descriptions, Western Electric Oscillator	10
III.	Swing Test Descriptions, Sulzer Oscillators	11
IV.	Effects of Temperature on Frequency Stability of Sulzer Oscillators	12
V.	Test Results for Western Electric 0-76A/U Oscillator, Serial No. 43	23
VI.	Test Results for Sulzer Model 2.5 Frequency Standard, Serial No. 256	28
VII.	Test Results for Sulzer Model D5 Oscillator Serial No. 25	33
VIII.	Test Results for Sulzer Model D5 Oscillator Serial No. 19	40
IX.	Test Results for Sulzer Model D5 Oscillator Serial No. 22	47

Table 1

No.	Description	Value
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

LIST OF ILLUSTRATIONS

Figure		Page
1.	Basic Test System	6
2.	Basic Test System Extended for Simultaneous Testing of Four Sulzer Oscillators	6
3.	Swing Platform, View One	7
4.	Swing Platform, View Two	7
5.	Sulzer D5 Oscillators Mounted on Shake Table	8
6.	Shock Testing Equipment	8
7.	Sample of Recorded Phase Comparator Output	13
8.	Sample Plot of Frequency Offset vs. Time	16
9.	Sample Plot of Frequency Offset vs. Time with Fitted Line and Standard Deviation, One-hour Intervals	17
10.	Sample Plot of Frequency Offset vs. Time with Fitted Line and Standard Deviation, One-half Hour Intervals	18
11.	Sample Plot of Frequency Offset vs. Time with Fitted Line and Standard Deviation, Two-hour Intervals	19
12.	Changes in Drift Rate of Western Electric 0-76A/U During Static Tests	24
13.	Changes in Stability of Western Electric 0-76A/U During Static Tests	25
14.	Changes in Drift Rate of Western Electric 0-76A/U During Swing Tests	26
15.	Changes in Stability of Western Electric 0-76A/U During Swing Tests	27
16.	Changes in Drift Rate of Sulzer Model 2.5 During Static Tests	29
17.	Changes in Stability of Sulzer Model 2.5 During Static Tests	30
18.	Changes in Drift Rate of Sulzer Model 2.5 During Swing Tests	31

Figure		Page
19.	Changes in Stability of Sulzer Model 2.5 During Swing Tests	32
20.	Changes in Drift Rate of Sulzer Model D5, Serial No. 25, During Static Tests	34
21.	Changes in Stability of Sulzer Model D5, Serial No. 25, During Static Tests	35
22.	Changes in Drift Rate of Sulzer Model D5, Serial No. 25, During Swing Tests	36
23.	Changes in Stability of Sulzer Model D5, Serial No. 25, During Swing Tests	37
24.	Changes in Drift Rate of Sulzer Model D5, Serial No. 25, During Vibration and Shock Tests	38
25.	Changes in Stability of Sulzer Model D5, Serial No. 25, During Vibration and Shock Tests	39
26.	Changes in Drift Rate of Sulzer Model D5, Serial No. 19, During Static Tests	41
27.	Changes in Stability of Sulzer Model D5, Serial No. 19, During Static Tests	42
28.	Changes in Drift Rate of Sulzer Model D5, Serial No. 19, During Swing Tests	43
29.	Changes in Stability of Sulzer Model D5, Serial No. 19, During Swing Tests	44
30.	Changes in Drift Rate of Sulzer Model D5, Serial No. 19, During Vibration and Shock Tests	45
31.	Changes in Stability of Sulzer Model D5, Serial No. 19, During Vibration and Shock Tests	46
32.	Changes in Drift Rate of Sulzer Model D5, Serial No. 22, During Static Tests	48
33.	Changes in Stability of Sulzer Model D5, Serial No. 22, During Static Tests	49
34.	Changes in Drift Rate of Sulzer Model D5, Serial No. 22, During Swing Tests	50

Figure		Page
35.	Changes in Stability of Sulzer Model D5, Serial No. 22, During Swing Tests	51
36.	Changes in Drift Rate of Sulzer Model D5, Serial No. 22, During Vibration and Shock Tests	52
37.	Changes in Stability of Sulzer Model D5, Serial No. 22, During Vibration and Shock Tests	53

100
101
102
103
104

THE
THE
THE
THE
THE

105
106
107
108
109

1. Introduction.

Due to improvements in crystal-unit and oscillator design and construction during the past ten years, it is now not unusual to speak of crystal oscillators with the capability of maintaining their frequency outputs constant to a few parts in 10^{10} or 10^{11} . Oscillators of this sort have been employed in very low frequency navigation systems, where the phenomenon of long-range, phase-stable VLF transmissions coupled with frequency-stable signals at the transmitters and aboard ship, permits a geographic position to be determined by a process of phase-comparison.

The accuracy of such a navigation system depends upon the frequency stability of the oscillators. It is recognized that environmental conditions such as temperature, vibration, and shock have a direct effect on the operation of crystal oscillators and, therefore, every effort is generally made to provide the operating conditions as specified by the manufacturer of the equipment.

In addition to the problems of temperature, vibration, and shock it was suspected that motion such as that created by the rolling and pitching of a ship or buoy might introduce instability.

It was the purpose of this investigation to determine the effects of such motion on the frequency stability of certain crystal oscillators as well as the effects of static position, vibration, and shock.

2. Oscillators Tested.

Tests were conducted with the following oscillators:

RF Oscillator 0-76A/U
Western Electric D-175730-L2 Frequency Standard
Serial No. 43

Sulzer Laboratories Model D5 Oscillator
Serial No. 25

Sulzer Laboratories Model D5 Oscillator
Serial No. 19

Sulzer Laboratories Model D5 Oscillator
Serial No. 22

Sulzer Laboratories Model 2.5 Frequency Standard
Serial No. 256

A brief description of each type of oscillator is given in the following paragraphs. Further information may be obtained from the equipment manuals furnished by the manufacturers. [1, 6, 7].

The Western Electric frequency standard produces a frequency of 100 kilocycles which, according to the manufacturer, can be maintained constant to within approximately one part in 10^8 per day. The crystal, a GT-cut quartz plate with a very low temperature coefficient, is maintained at a constant temperature by a two-stage oven and a bridge oscillator circuit. The oscillator weighs 90 pounds; its dimensions are 19" x 20" x 10".

The Sulzer Laboratories Model D5 oscillator is a solid-state unit with a five-megacycle output and a rated stability of five parts in 10^{10} per day. The crystal is an AT-cut quartz plate, vibrating in a fifth-overtone, thickness-shear mode. Temperature level is maintained by a two-stage oven. The oscillator weighs approximately

Published weekly, except on Sundays, by the American Medical Association, 535 North Dearborn Street, Chicago, Ill.

Subscription price, \$5.00 per annum in advance. Single copies, 15 cents. Entered as second-class matter, May 2, 1912. Postpaid.

Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 1, 1920.

Copyright, 1921, by American Medical Association. Printed at the American Medical Association Press, Chicago, Ill.

Published by the American Medical Association, 535 North Dearborn Street, Chicago, Ill.

Subscription price, \$5.00 per annum in advance. Single copies, 15 cents. Entered as second-class matter, May 2, 1912. Postpaid.

and is published weekly, except on Sundays, by the American Medical Association, 535 North Dearborn Street, Chicago, Ill.

Subscription price, \$5.00 per annum in advance. Single copies, 15 cents. Entered as second-class matter, May 2, 1912. Postpaid.

$\int_0^1 f(x) dx$ is the area under the curve $y=f(x)$ from $x=0$ to $x=1$. The area is positive if the curve is above the x -axis and negative if it is below the x -axis.

The area under the curve $y=f(x)$ from $x=a$ to $x=b$ is denoted by $\int_a^b f(x) dx$.

The area under the curve $y=f(x)$ from $x=a$ to $x=b$ is denoted by $\int_a^b f(x) dx$.

The area under the curve $y=f(x)$ from $x=a$ to $x=b$ is denoted by $\int_a^b f(x) dx$.

The area under the curve $y=f(x)$ from $x=a$ to $x=b$ is denoted by $\int_a^b f(x) dx$.

The area under the curve $y=f(x)$ from $x=a$ to $x=b$ is denoted by $\int_a^b f(x) dx$.

The area under the curve $y=f(x)$ from $x=a$ to $x=b$ is denoted by $\int_a^b f(x) dx$.

The area under the curve $y=f(x)$ from $x=a$ to $x=b$ is denoted by $\int_a^b f(x) dx$.

The area under the curve $y=f(x)$ from $x=a$ to $x=b$ is denoted by $\int_a^b f(x) dx$.

The area under the curve $y=f(x)$ from $x=a$ to $x=b$ is denoted by $\int_a^b f(x) dx$.

The area under the curve $y=f(x)$ from $x=a$ to $x=b$ is denoted by $\int_a^b f(x) dx$.

The area under the curve $y=f(x)$ from $x=a$ to $x=b$ is denoted by $\int_a^b f(x) dx$.

The area under the curve $y=f(x)$ from $x=a$ to $x=b$ is denoted by $\int_a^b f(x) dx$.

three and one-half pounds; its dimensions are $4\frac{1}{2}" \times 4\frac{1}{2}" \times 6 \frac{7}{8}"$.

The third type of oscillator tested, a Sulzer Laboratories Model 2.5 frequency standard, is also a solid-state unit. It has frequency outputs of two and one-half megacycles, one megacycle, and 100 kilocycles. Stability as stated by the manufacturer is one part in 10^{10} or better per day. The crystal-unit is a two and one-half megacycle military-type designed by Warner of Bell Telephone Laboratories. It is mounted in a proportionally-controlled double oven. The oscillator weighs approximately six and one-half pounds; its dimensions are $4\frac{1}{2}" \times 4\frac{1}{2}" \times 11 \frac{3}{4}"$.

3. Test Program.

Purpose and Procedure

The purpose of the testing program was to reveal the effects of static position, swinging motion, vibration, and shock on the frequency stability of the crystal oscillators described above. To accomplish this goal, each of the oscillators was subjected to certain conditions and combinations of position and motion while a constant observation was made of its frequency output.

The frequency standard employed as a reference for the tests was a Varian Model V-4700 Rubidium Vapor Frequency Standard with a long term frequency stability of 5×10^{-11} in any one-year period (standard deviation). To insure the reliability of the standard during the test period, its output was continually phase-compared against the 20 kilocycle signal of WWVL. This comparison was made with a Textran Series 599 VLF Tracking Receiver. The stability during the period from 23 July 1965 to 1 November 1965 was 2.3×10^{-11} (standard deviation).

The output of the test oscillator was phase-compared against the Rubidium standard and the output of the phase comparator was recorded on a strip chart recorder. The basic test system is shown in Figure 1. Examination and processing of the recorded data produced the results presented in Section 5.

THEORY OF THE EARTH

The theory of the earth is a branch of geology which deals with the origin and development of the earth and its various parts. It is a science which seeks to explain the causes of the various geological phenomena which we observe in nature. The theory of the earth is a very old science, and it has been the subject of much speculation and controversy. In the early days of the world, men believed that the earth was created by the gods, and that it was the work of the gods to create the world. But as time went on, men began to think for themselves, and they began to ask questions about the origin of the earth. They began to wonder how the earth came to be, and what caused the various geological phenomena which they observed. This led to the development of the theory of the earth, which is a science which seeks to explain the causes of the various geological phenomena which we observe in nature.

The theory of the earth is a very old science, and it has been the subject of much speculation and controversy. In the early days of the world, men believed that the earth was created by the gods, and that it was the work of the gods to create the world. But as time went on, men began to think for themselves, and they began to ask questions about the origin of the earth. They began to wonder how the earth came to be, and what caused the various geological phenomena which they observed. This led to the development of the theory of the earth, which is a science which seeks to explain the causes of the various geological phenomena which we observe in nature.

Circuits and Equipment

While the test circuit was basically that shown in Figure 1, the laboratory hook-up was more complicated due to the simultaneous testing of as many as four oscillators. All phase comparisons were made at 100 kilocycles, necessitating the use of frequency dividers in the case of the Sulzer D5's with their five-megacycle outputs. The phase comparators, frequency dividers, and oscillators also required separate power supplies. Figure 2 shows an extension of the basic test system for the case of four oscillators under test.

A thermistor-bridge circuit and a chart recorder were employed to maintain a constant record of room temperature for the duration of the tests.

Swinging motion was provided by a specially constructed swinging platform shown in Figures 3 and 4. The swing was driven by a three-quarter horsepower electric motor coupled to a hydraulic transmission. The transmission permitted adjustment of swing frequency and the slotted drive wheel permitted adjustment of swing amplitude.

Vibration was accomplished with a Goodmans Model 390 A Vibration Generator. A low-frequency function generator and a power amplifier were used to supply the necessary input. The shake table with the three Sulzer D5 oscillators mounted on it is shown in Figure 5.

Figure 6 illustrates the equipment used to provide a periodic lift-and-release motion for the shock testing described in a later paragraph. The equipment consisted of a direct-current motor with a cam attached to its shaft, and geared for high-torque, slow-speed

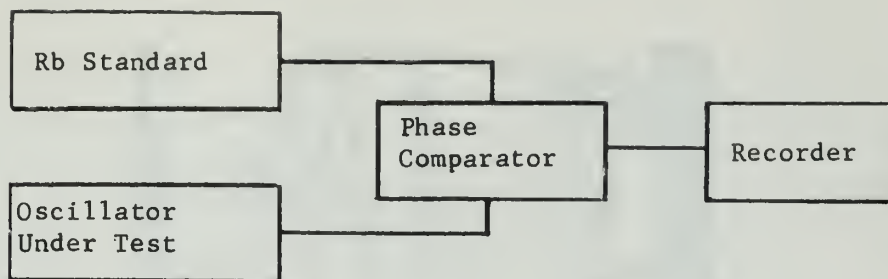


FIGURE 1
BASIC TEST SYSTEM

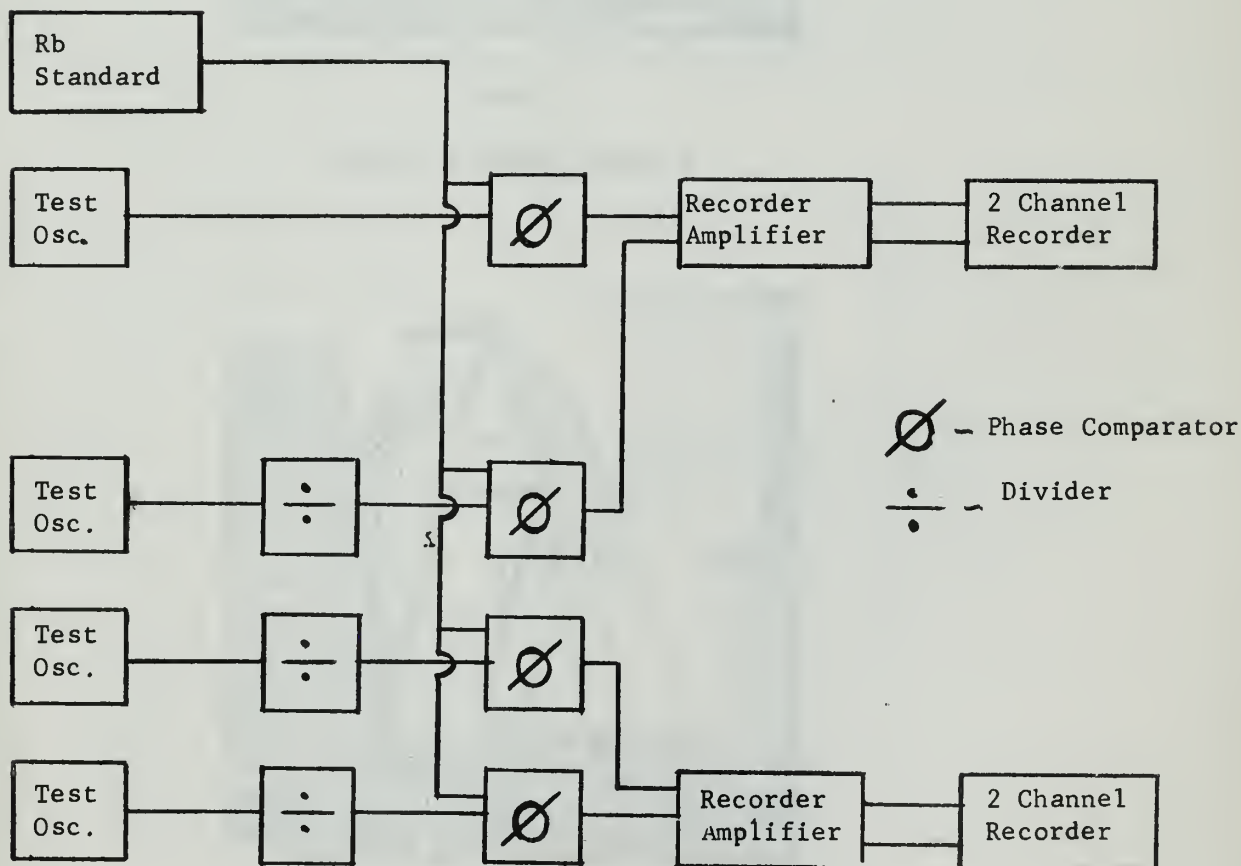


FIGURE 2
BASIC TEST SYSTEM EXTENDED FOR
SIMULTANEOUS TESTING OF FOUR SULZER OSCILLATORS

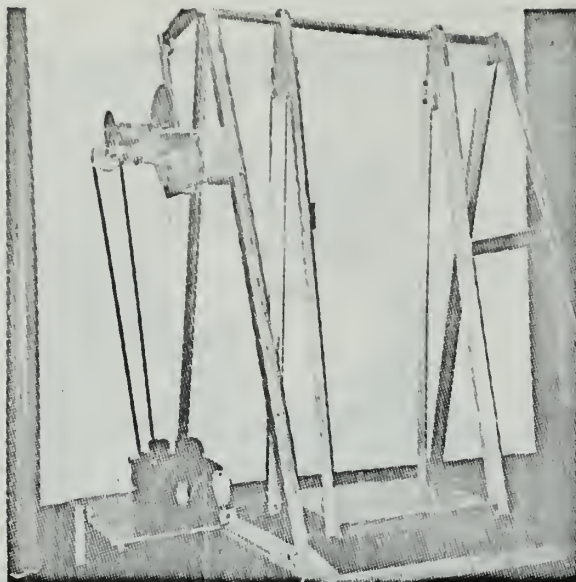


FIGURE 3

SWING PLATFORM, VIEW 1

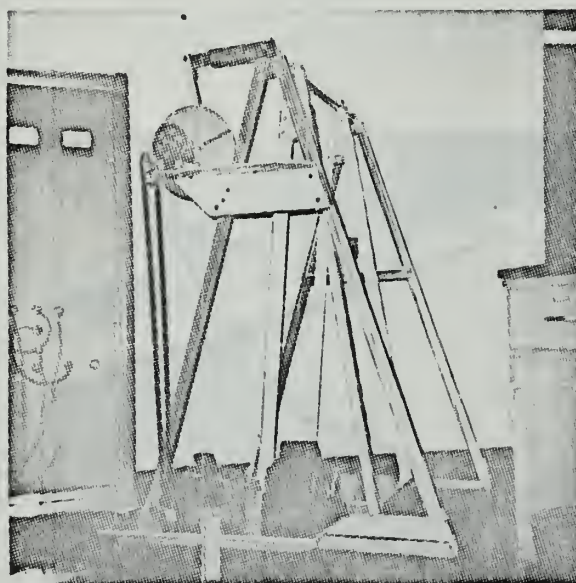


FIGURE 4

SWING PLATFORM, VIEW 2



FIGURE 5

SULZER D5 OSCILLATORS MOUNTED ON SHAKE TABLE

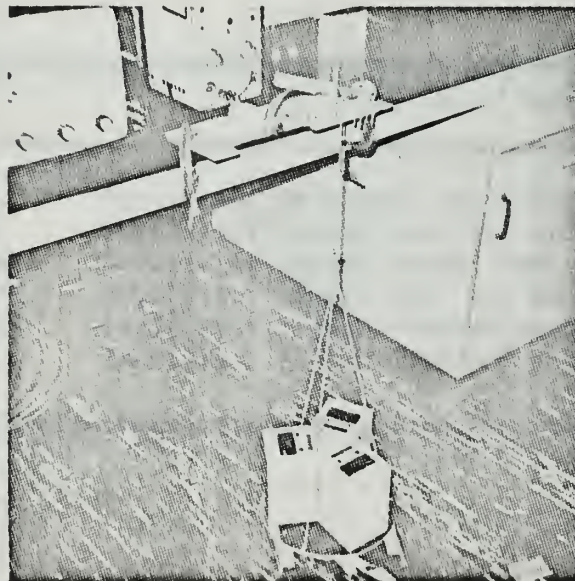


FIGURE 6

SHOCK TESTING EQUIPMENT



Figure 1
 Aerial view of the study area



Figure 2
 Aerial view of the study area

operation. The cam periodically lifted and released a hinged bar from which was suspended the mounting platform for the oscillators.

Description of Tests

Static Tests. The static tests consisted of operating the test oscillator for at least 48 hours on each of its six sides. The oscillator was operated first in its normal position, then rotated counterclockwise through the side, upside down, and side positions. It was then operated on each of the remaining two sides. After 48 hours in each of these positions, the oscillator was returned to its normal position for an additional 48 hours of testing. These tests were conducted on all of the oscillators. Table I lists the various static tests and their descriptions.

TABLE I
STATIC TEST DESCRIPTIONS

Test	Oscillator Position
Static One	Oscillator in normal operating position
Static Two	Oscillator tipped onto its side
Static Three	Oscillator tipped upside down
Static Four	Oscillator tipped onto its side
Static Five	Oscillator tipped forward onto its face
Static Six	Oscillator tipped backward onto its back

Swing Tests. These tests were also conducted over a basic 48 hour test period. The test oscillator or oscillators were fastened to the swing platform and the swing was then placed in motion. The Western Electric 0-76A/U was swung at various amplitudes and frequencies in one position only, the normal position, with the front panel of the oscillator parallel to the leading edge of the swing platform and perpendicular to the line of motion. The four Sulzer oscillators were swung simultaneously, and in two positions, the first being identical to that described for the 0-76A/U. For the second position, the oscillators were rotated 90° in the plane of the platform. The period and amplitude of the various tests are given in Tables II and III.

TABLE II
SWING TEST DESCRIPTIONS,
WESTERN ELECTRIC OSCILLATOR

Test	Amplitude*	Period
Swing One	$10^{\circ}, 10^{\circ}$	30 seconds
Swing Two	$10^{\circ}, 10^{\circ}$	10 seconds
Swing Three	$20^{\circ}, 20^{\circ}$	30 seconds
Swing Four	$5^{\circ}, 5^{\circ}$	30 seconds
Swing Five	$5^{\circ}, 5^{\circ}$	10 seconds
Swing Six	$10^{\circ}, 10^{\circ}$	20 seconds

* $10^{\circ}, 10^{\circ}$ represents a symmetric swing of 10° off the vertical in each direction.

TABLE III
SWING TEST DESCRIPTIONS,
SULZER OSCILLATORS

Test	Amplitude*	Period
First Position:		
Swing One	5 ^o , 10 ^o	30 seconds
Swing Two	5 ^o , 10 ^o	10 seconds
Swing Three	24 ^o , 30 ^o	30 seconds
Swing Four	24 ^o , 30 ^o	10 seconds
Second Position:		
Swing Five	5 ^o , 10 ^o	30 seconds
Swing Six	5 ^o , 10 ^o	10 seconds
Swing Seven	24 ^o , 30 ^o	30 seconds
Swing Eight	24 ^o , 30 ^o	10 seconds

*5^o, 10^o represents an asymmetric swing of 5^o off vertical in one direction and 10^o off vertical in the opposite direction

Vibration Test. This test was conducted only with the Sulzer D5 oscillators. The oscillators were mounted on a one-quarter inch thick aluminum plate with a diameter of twelve inches which was then attached to the vibration generator (see Figure 5). They were vibrated simultaneously at a frequency of 20 cycles per second with a force of approximately one g for a period of 12 hours. After a 12 hour quiet period, the oscillators were once again subjected to the same vibration condition for a period of ten hours.

Shock Test. The shock, or impact, test was also conducted only with the Sulzer D5 oscillators. The test consisted of a free fall from a height of three-tenths of an inch onto asphalt tile laid on

concrete (see Figure 6). As in the vibration test, all three oscillators were tested simultaneously. Impacting occurred at a rate of once every ten seconds and was conducted continuously for 12 hours.

Environment. All tests were conducted in an open laboratory with room temperature normally ranging daily from 21°C to 23°C. Over the 43 day test period the mean temperature was 22°C with a low of 18°C and a high of 29°C.

Data furnished by Sulzer Laboratories with respect to effects of temperature change on frequency stability of the Sulzer oscillators is shown in Table IV. Similar data for the Western Electric oscillator was not available.

TABLE IV
EFFECTS OF TEMPERATURE ON
FREQUENCY STABILITY OF SULZER OSCILLATORS*

Oscillator	Temperature Change	Maximum $\frac{\Delta f^{**}}{F}$
Model 2.5 Frequency Standard	ambient temperature 20°C changed $\pm 15^\circ\text{C}$	$\pm 2 \times 10^{-10}$
Model D5	ambient temperature -54°C vs + 25°C	$\pm 1 \times 10^{-9}$
Model D5	ambient temperature -18°C vs + 25°C	$\pm 5 \times 10^{-10}$
Model D5	ambient temperature +60°C vs + 25°C	$\pm 5 \times 10^{-10}$
Model D5	ambient temperature +65°C vs + 25°C	$\pm 1 \times 10^{-9}$

*Information furnished by Sulzer Laboratories

**Defined on Page 14

4. Data Acquisition and Processing.

Acquisition

During the course of each test, the outputs of the various phase comparators were fed to strip chart recorders which provided a permanent data record for processing and analysis at a later date. Temperature data was also permanently recorded. The phase-comparison data was in the form shown in Figure 7.

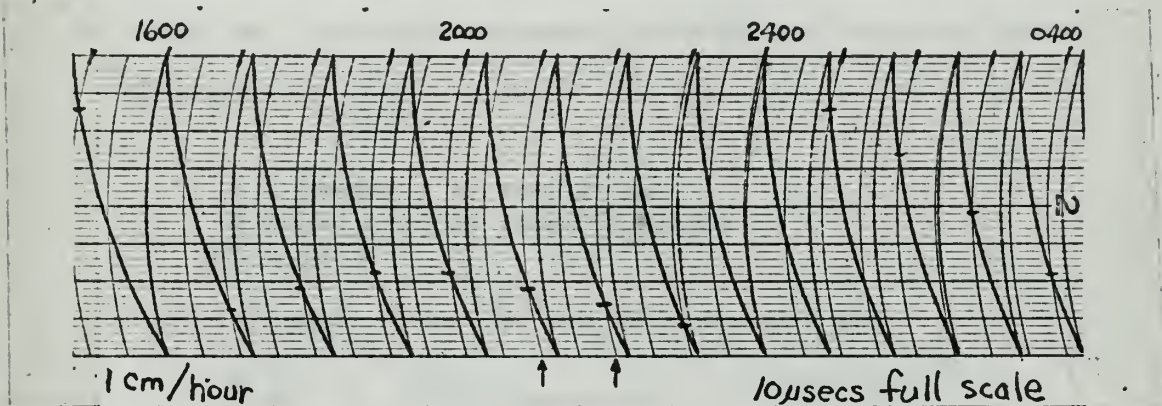


FIGURE 7

SAMPLE OF RECORDED PHASE COMPARATOR OUTPUT

The output of a phase comparator indicated the difference between the frequencies of the two input signals. If the frequencies of the signals were equal, the phase difference of the signals was constant, and the output of the phase comparator was constant. If the frequencies were not equal, however, the signals passed in and out of phase with each other periodically and the cyclic change in phase difference produced a similar variation in the phase comparator output. By recording this cyclic output on a strip-chart moving at a regulated speed, the rate of phase shift, cycles/unit time, was determined. For example, as shown in Figure 7, during the period from 2100 to 2200

RECEIVED AT THE UNIVERSITY OF CHICAGO LIBRARY

ON MAY 15 1968

FROM THE UNIVERSITY OF CHICAGO LIBRARY

TO THE UNIVERSITY OF CHICAGO LIBRARY

ON MAY 15 1968

FROM THE UNIVERSITY OF CHICAGO LIBRARY

TO THE UNIVERSITY OF CHICAGO LIBRARY

ON MAY 15 1968

FROM THE UNIVERSITY OF CHICAGO LIBRARY

TO THE UNIVERSITY OF CHICAGO LIBRARY

ON MAY 15 1968

FROM THE UNIVERSITY OF CHICAGO LIBRARY

TO THE UNIVERSITY OF CHICAGO LIBRARY

ON MAY 15 1968

FROM THE UNIVERSITY OF CHICAGO LIBRARY

TO THE UNIVERSITY OF CHICAGO LIBRARY

ON MAY 15 1968

FROM THE UNIVERSITY OF CHICAGO LIBRARY

TO THE UNIVERSITY OF CHICAGO LIBRARY

ON MAY 15 1968

FROM THE UNIVERSITY OF CHICAGO LIBRARY

TO THE UNIVERSITY OF CHICAGO LIBRARY

ON MAY 15 1968

FROM THE UNIVERSITY OF CHICAGO LIBRARY

TO THE UNIVERSITY OF CHICAGO LIBRARY

ON MAY 15 1968

FROM THE UNIVERSITY OF CHICAGO LIBRARY

TO THE UNIVERSITY OF CHICAGO LIBRARY

ON MAY 15 1968

the phase comparator passed through 1.05 cycles; the rate of phase shift during this period was 1.05 cycles/hour.

All phase comparison was done at a frequency of 100 kilocycles. Therefore, during the one-hour period, the standard signal went through $3600 \times 100,000$ or 3.6×10^8 cycles while the test signal went through $3.6 \times 10^8 - 1.05$ cycles.

The difference between the frequencies, expressed as a fraction, is called the fractional frequency error or the frequency offset.

It is written as $\frac{\Delta f}{F}$ where

f = frequency of test signal

F = frequency of standard signal

$\Delta f = f - F$

The frequency offset for the above example was

$$\frac{\Delta f}{F} = \frac{-1.05}{3.6 \times 10^8} = -2.9 \times 10^{-9}$$

It is customary to refer to the amount of phase shift in terms of time rather than frequency. At 100 kilocycles, the time for one cycle is ten micro-seconds and 1.05 cycles of phase shift per hour is equivalent to 10.5 micro-seconds of phase shift per hour. The frequency offset may then also be computed as

$$\frac{\Delta f}{F} = \frac{\Delta t}{T} = \frac{-10.5 \times 10^{-6}}{3600} = -2.9 \times 10^{-9}$$

where T = period of observation in seconds

Δt = phase shift in seconds occurring during T

Processing

The recorded data for each test was examined in the manner outlined above. The number of micro-seconds of phase shift per hour

was noted for each hour of each test period. These figures were used to compute hourly values of frequency offset, $\Delta f/F$, which were then plotted versus time. A sample plot is shown in Figure 8. The positive values of frequency offset indicate that the frequency of the test oscillator was above that of the standard. The upward drift of the points represents an increase in frequency of the test oscillator. This is a normal condition, caused by aging of the crystal.

Next, a digital computer was employed to fit a straight line to the plotted points and to measure the dispersion of the points about this fitted line by computing their standard deviation. The program used for these computations is given in the Appendix. The slope of the fitted line represented the frequency drift rate of the test oscillator and the standard deviation of the points was an indicator of the oscillator's frequency stability, with lower values of standard deviation indicating better stability. Figure 9 shows the sample plot presented in Figure 8 with a straight line fitted to the points. The choice of a one-hour interval between the points was purely arbitrary. Figures 10 and 11 present the same data plotted at intervals of one-half hour and two hours respectively. It may be noted that the smallest variation of $\Delta f/F$ plotted in Figure 9 is 7×10^{-11} ; in Figure 10, 14×10^{-11} ; and in Figure 11, 3.5×10^{-11} . This is because the smallest value of $\Delta f/F$ is inversely proportional to the length of the observation interval. Using the 40-line chart paper shown in Figure 7, with the recorder calibrated for ten

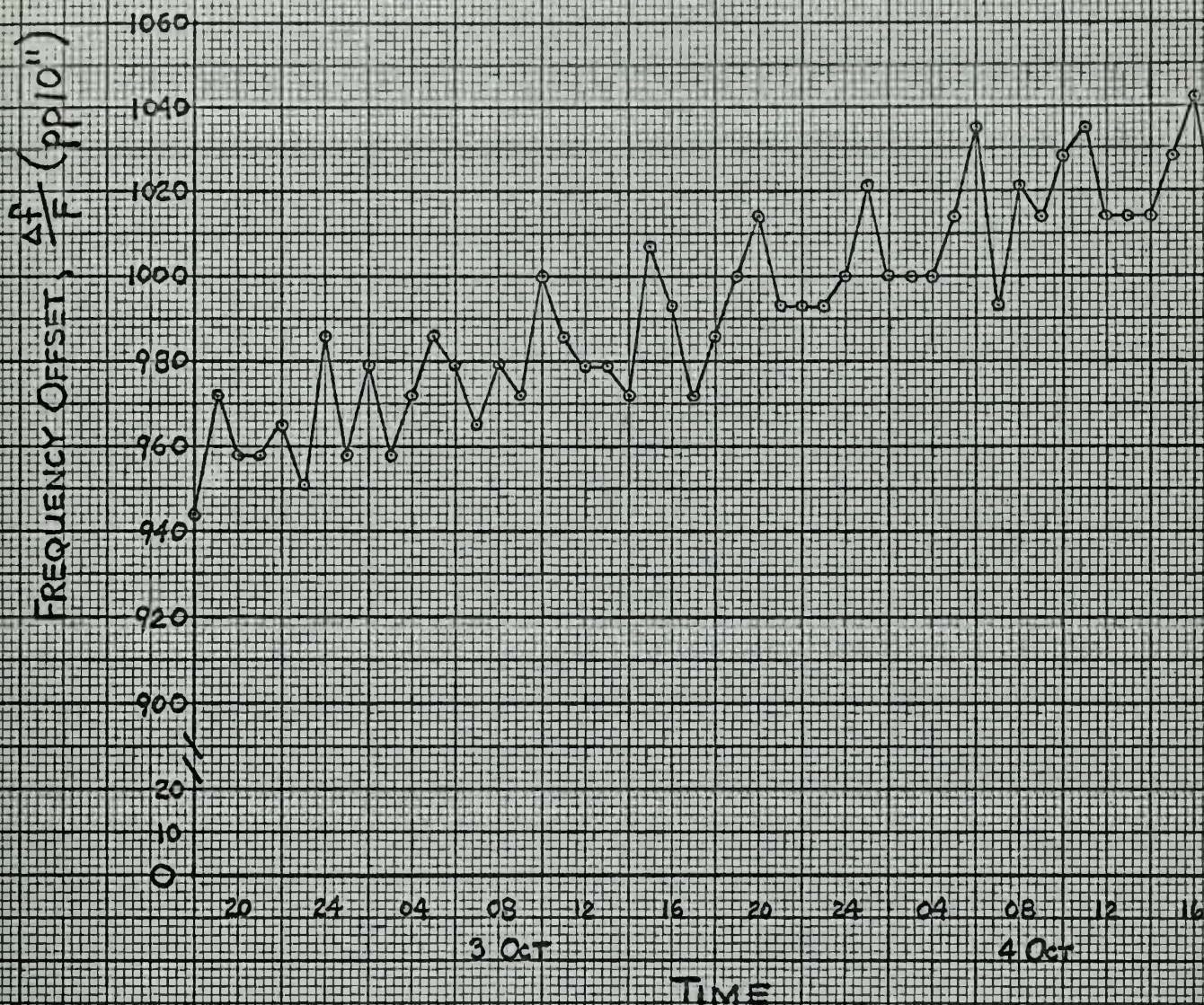


FIGURE 8
SAMPLE PLOT OF
FREQUENCY OFFSET VS TIME

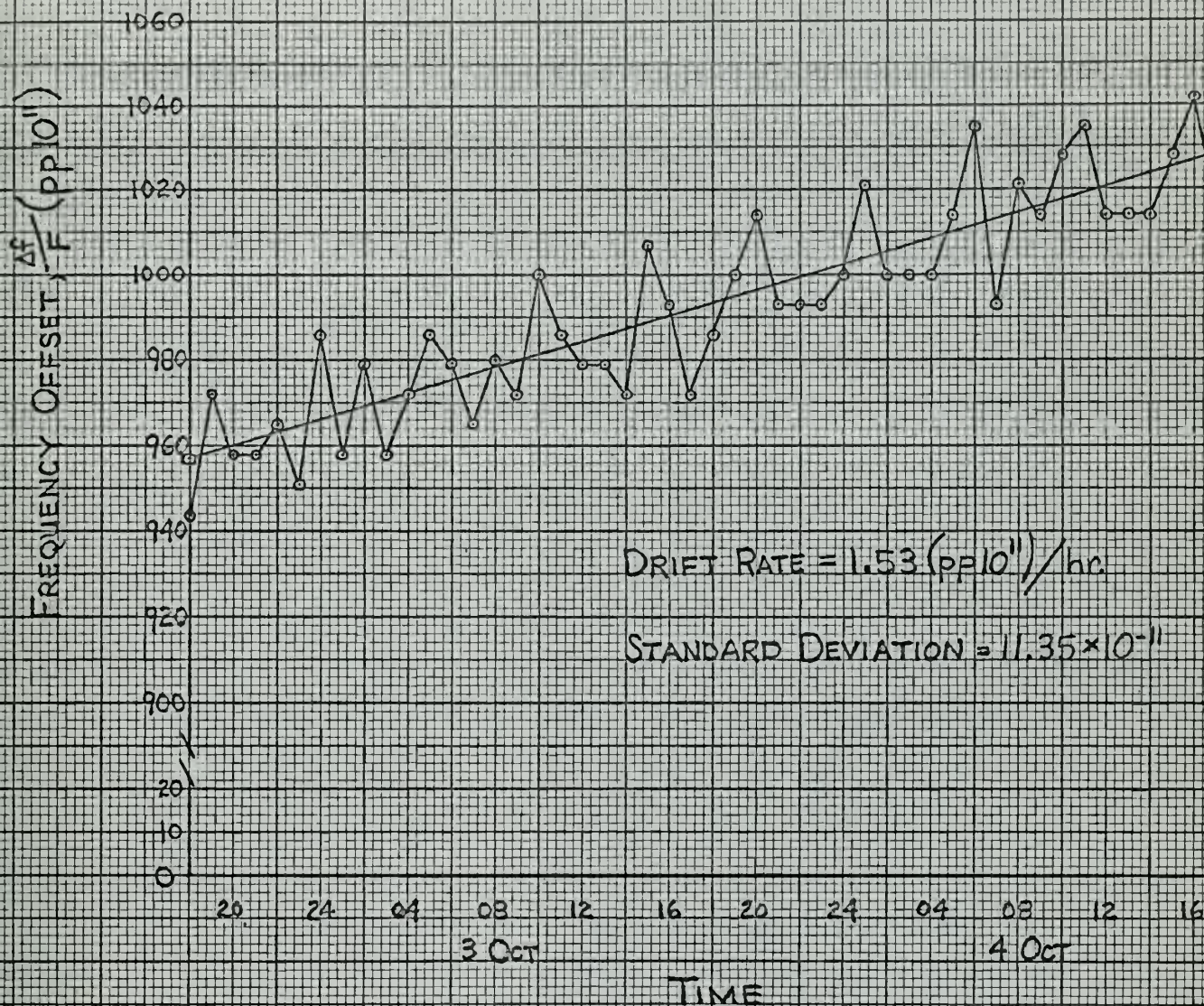


FIGURE 9
 SAMPLE PLOT OF
 FREQUENCY OFFSET VS TIME
 WITH FITTED LINE AND
 STANDARD DEVIATION,
 ONE-HOUR INTERVALS



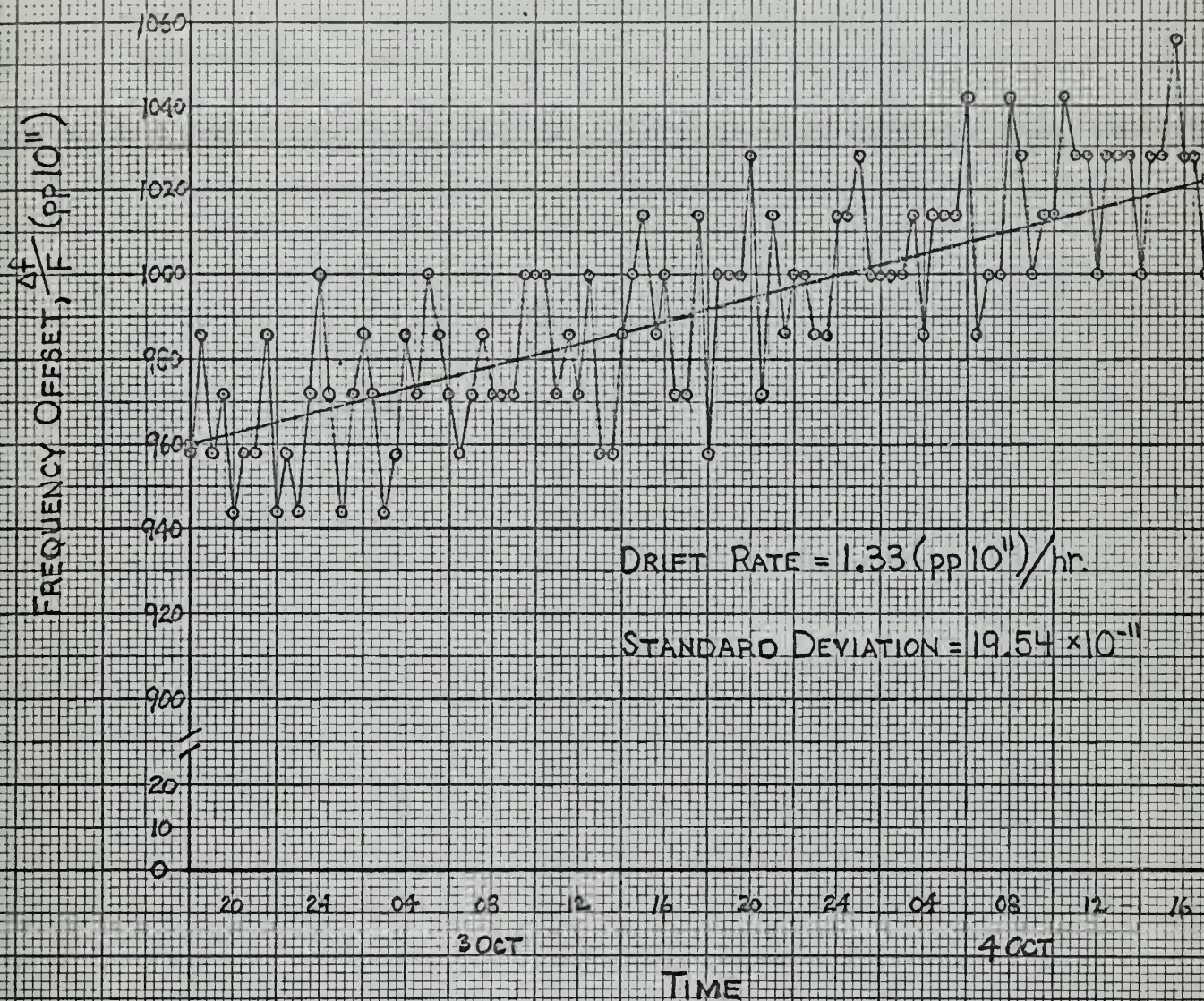


FIGURE 10

SAMPLE PLOT OF
 FREQUENCY OFFSET VS TIME
 WITH FITTED LINE AND
 STANDARD DEVIATION,
 ONE-HALF HOUR INTERVALS

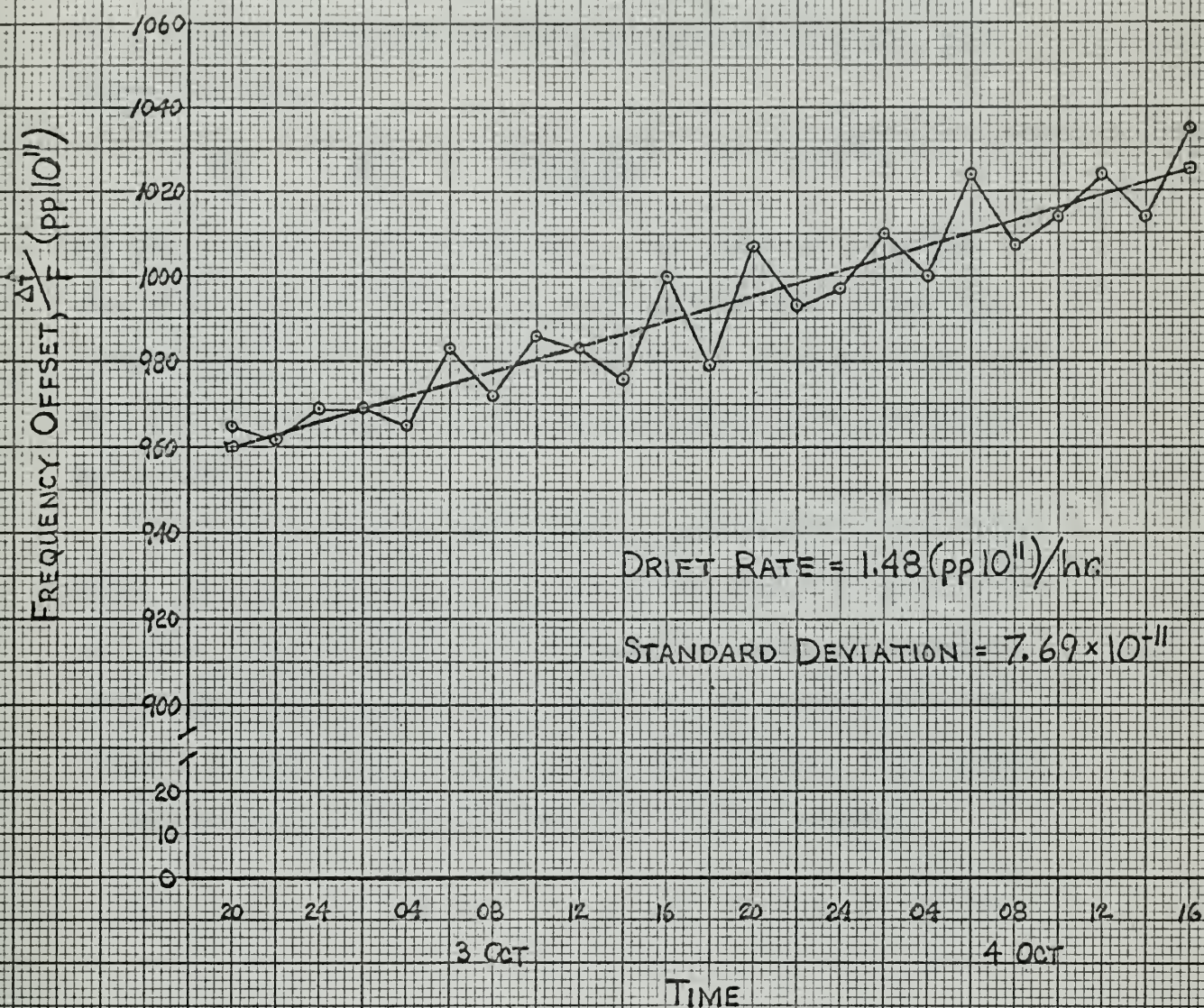


FIGURE 11

SAMPLE PLOT OF
 FREQUENCY OFFSET VS TIME
 WITH FITTED LINE AND
 STANDARD DEVIATION,
 TWO-HOUR INTERVALS

micro-seconds of phase shift for full scale deflection, the smallest increment of phase shift readable is 0.25 micro-second. Therefore, for a one-hour observation interval, the smallest value of $\Delta f/F$ (other than zero) is

$$\frac{\Delta f}{F} = \frac{\Delta t}{T} = \frac{0.25 \times 10^{-6}}{3600} = 7 \times 10^{-11}$$

For the purposes of this investigation, the choice of a one-hour observation interval proved to be quite satisfactory. Additional accuracy could have been obtained, however, by using recording equipment with 100-line paper, permitting phase shift to be read to 0.1 micro-second.

In summary, the data processing was accomplished in three steps. First, the strip charts were examined for the amount of phase shift per hour. Second, this data was converted to values of frequency offset and plotted against time. Third, to the plotted points was fitted a straight line, whose slope was thus obtained, and a measure of the variation of the points about the line was computed.

THE UNIVERSITY OF CHICAGO
DEPARTMENT OF CHEMISTRY
530 SOUTH EAST ASIAN AVENUE
CHICAGO, ILLINOIS 60607-7070

THE UNIVERSITY OF CHICAGO PRESS
530 SOUTH EAST ASIAN AVENUE
CHICAGO, ILLINOIS 60607-7070

THE UNIVERSITY OF CHICAGO PRESS
530 SOUTH EAST ASIAN AVENUE
CHICAGO, ILLINOIS 60607-7070
THE UNIVERSITY OF CHICAGO PRESS
530 SOUTH EAST ASIAN AVENUE
CHICAGO, ILLINOIS 60607-7070

THE UNIVERSITY OF CHICAGO PRESS
530 SOUTH EAST ASIAN AVENUE
CHICAGO, ILLINOIS 60607-7070
THE UNIVERSITY OF CHICAGO PRESS
530 SOUTH EAST ASIAN AVENUE
CHICAGO, ILLINOIS 60607-7070
THE UNIVERSITY OF CHICAGO PRESS
530 SOUTH EAST ASIAN AVENUE
CHICAGO, ILLINOIS 60607-7070

5. Test Results.

The results of all tests are presented in Tables V through IX and Figures 12 through 37. The complete testing program of static, swinging motion, vibration, and shock tests was conducted with only the three Sulzer Model D5 oscillators. The two frequency standards were not subjected to vibration and shock.

Prior to the arrival of the Sulzer equipment, static and swinging motion tests were begun with two Western Electric frequency standards. One of these was the oscillator mentioned in Section 2, a model 0-76A/U, and the second was an earlier model, 076/U. It was soon determined that the drift rate and frequency stability of the older 0-76/U were affected by fluctuations in room temperature. The combined weight of the two oscillators (approximately 180 pounds) also proved to be too great a load for the swing platform and prevented simultaneous swing testing. A circuit failure in the 0-76/U, coupled with the problems of its poor stability and load on the swing, caused testing with this particular oscillator to be discontinued. The 0-76A/U, however, was unaffected by changes in room temperature and operated properly during the test period.

The results of the static and swing tests for this oscillator are given in Table V and Figures 12 through 15. In some instances the movement of the oscillator from one static position to another created a temporary frequency disturbance and several hours were required for the drift rate to return to its former state.

During this recovery period the change in frequency offset was relatively rapid and therefore the total test period was divided into sections to permit better fitting of straight lines to the data points. The three highest values of drift rate plotted in Figure 12, and the three highest values of standard deviation plotted in Figure 13, occurred during the recovery periods. For reference purposes the oscillator was operated in the Static One or normal position at the beginning and end of both the static test series and swing test series. The "motor only" entry in Table V refers to a period when the swing drive was disconnected and the swing platform was at rest, but the drive motor was running. This particular test was conducted to check for possible effects of vibration generated by the motor and hydraulic transmission.

After a three-week warm-up period, the new Sulzer equipment was tested. It was recognized that this was an inadequate warm-up time, but the late arrival of the equipment and the pressure of time made it mandatory to begin the tests. The results of these tests are given in Tables VI through IX and Figures 16 through 37. The room temperature variations had no noticeable effect on the drift rate or frequency stability of these oscillators.

TABLE V
TEST RESULTS FOR
WESTERN ELECTRIC 0-76A/U OSCILLATOR
SERIAL NO. 43

Test	Condition	Length (Hours)	Drift Rate $\frac{\Delta f}{F}$ (pp 10^9) hour	Standard Deviation (x 10^9)
Static 1	normal	48	0.110	0.35
Static 2 (a)	side	24	0.473	1.05
Static 2 (b)	side	24	0.141	0.53
Static 3	upside down	48	0.143	0.87
Static 4	side	40	0.172	0.53
Static 5 (a)	front	12	0.835	1.12
Static 5 (b)	front	36	0.053	0.44
Static 6 (a)	back	6	1.494	1.11
Static 6 (b)	back	20	0.237	0.49
Static 6 (c)	back	22	0.144	0.43
Static 1	normal	48	0.102	0.82
Static 1	normal	192	0.037	0.57
Static 1	normal	158	0.025	0.41
Swing 1	10°, 10°, 30 sec.*	48	0.133	0.80
Swing 2	10°, 10°, 10 sec.	48	0.033	0.80
Swing 3	20°, 20°, 30 sec.	48	0.031	0.72
Swing 4	5°, 5°, 30 sec.	48	-0.003	0.86
Swing 5	5°, 5°, 10 sec.	48	0.047	1.29
Swing 6	10°, 10°, 20 sec.	48	-0.037	0.81
Static 1 (motor only)	normal	48	0.039	0.67
Static 1	normal	48	0.127	0.96
Static 1	normal	48	0.033	0.60
Static 1	normal	97	0.025	0.73

*10°, 10°, 30 sec. represents a symmetric swing of 10° off the vertical in each direction with a 30-second period.

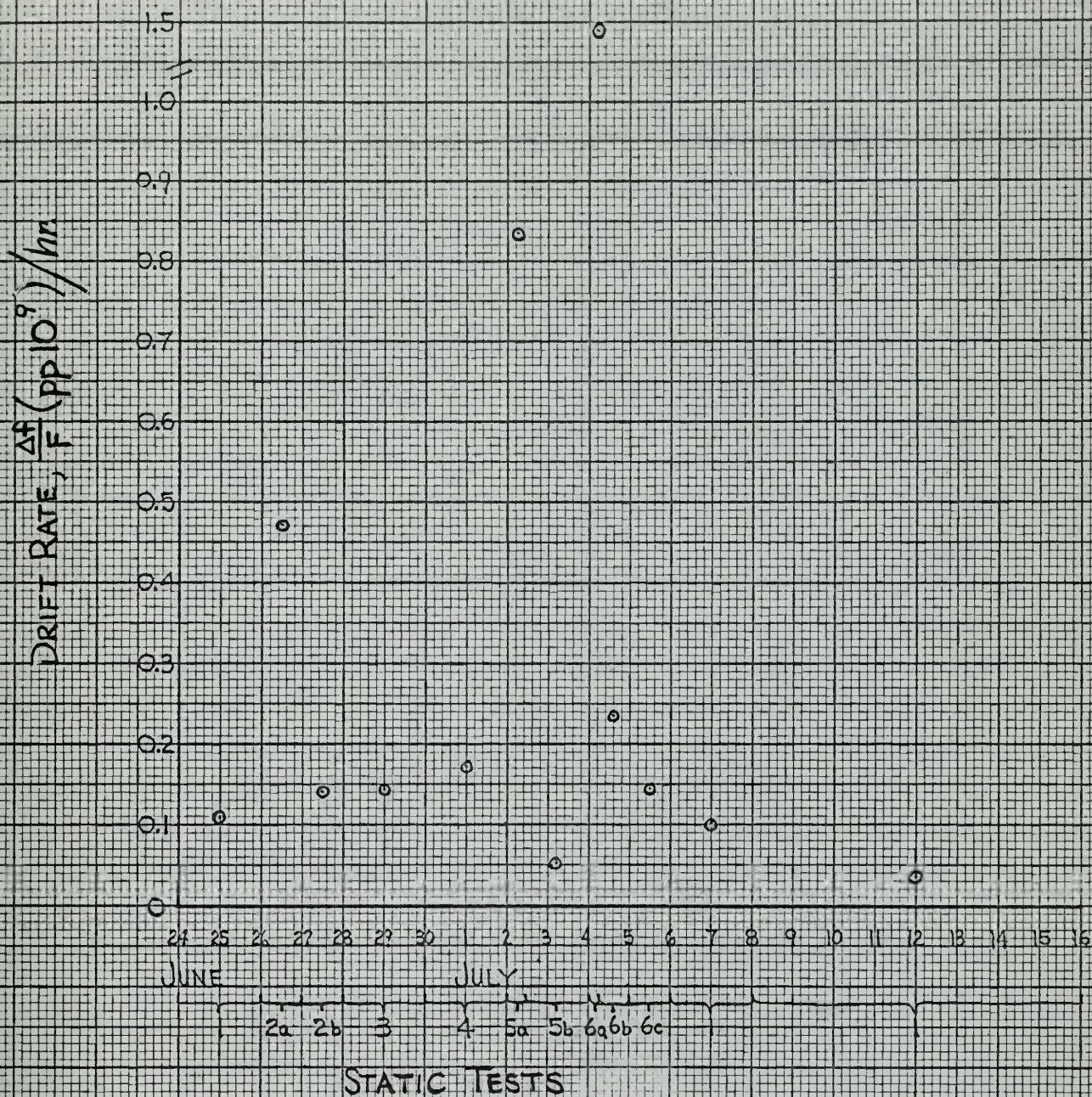
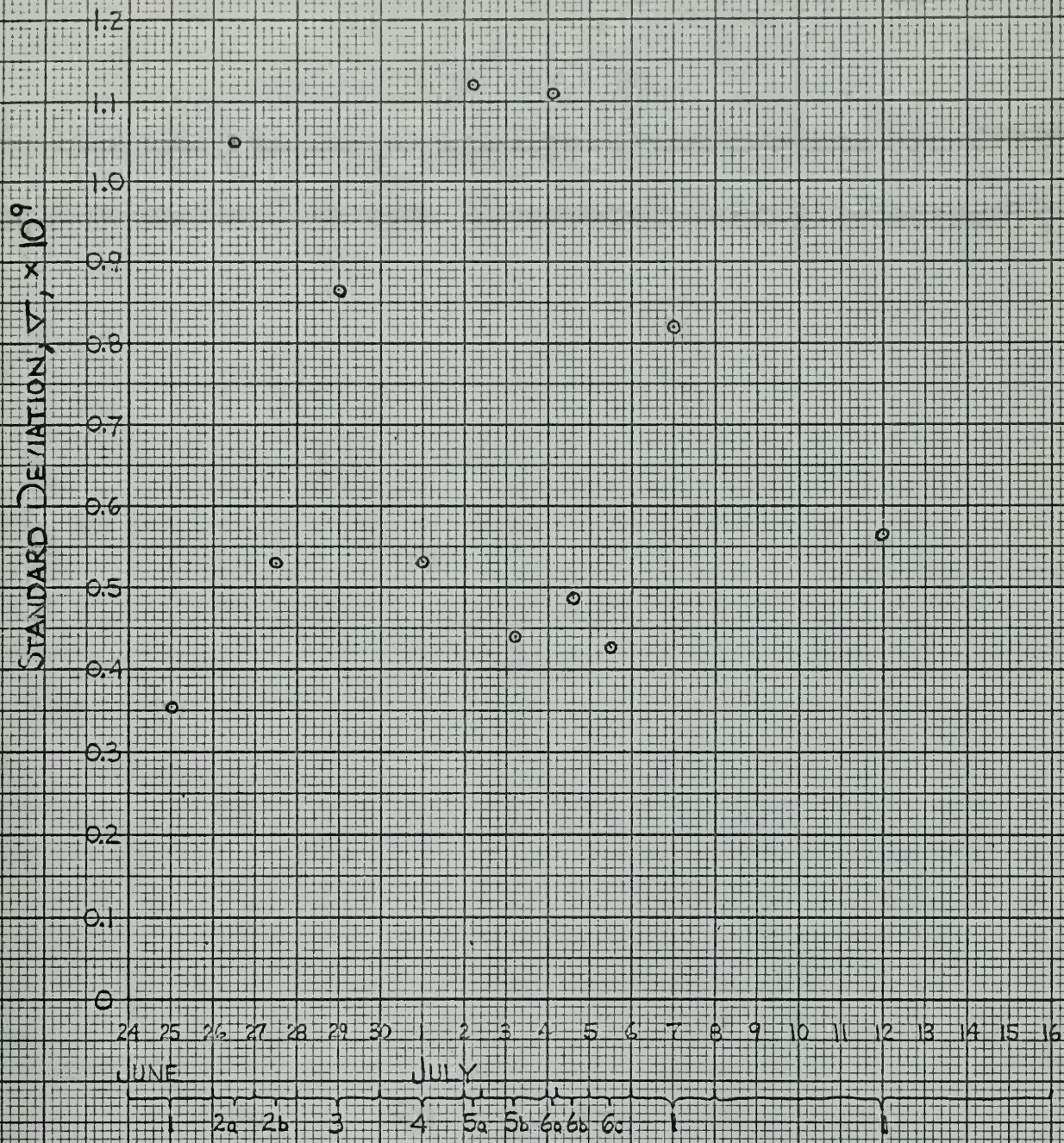


FIGURE 12
CHANGES IN DRIET RATE OF
WESTERN ELECTRIC 0-76A/U
DURING STATIC TESTS





STATIC TESTS

FIGURE 13

CHANGES IN STABILITY OF
WESTERN ELECTRIC O-76A/U
DURING STATIC TESTS

DRIFT RATE, $\frac{\Delta F}{F} (pp10^9)/hr$

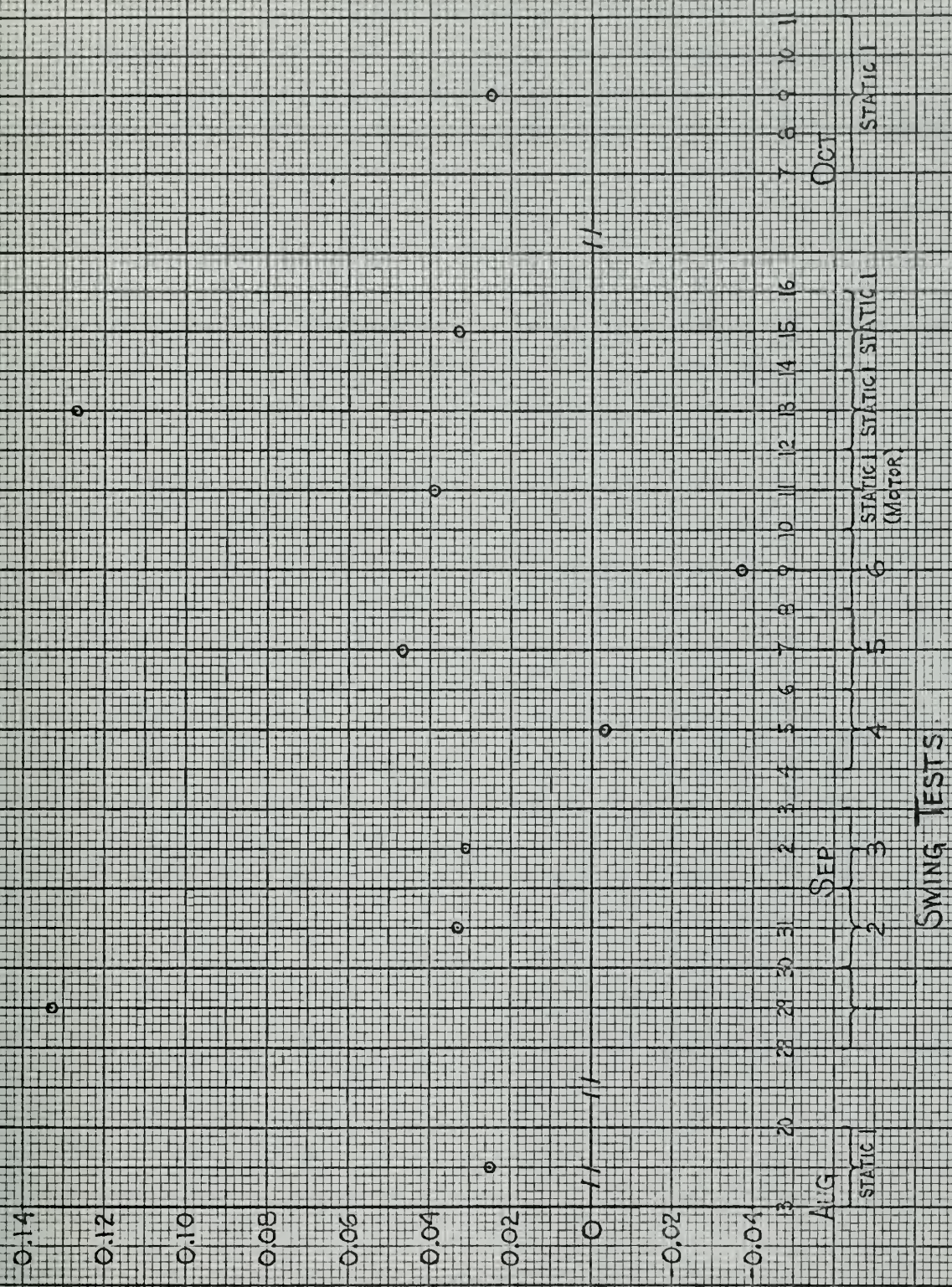


FIGURE 14

CHANGES IN DRIFT RATE OF
WESTERN ELECTRIC 0-76A/u
DURING SWING TESTS

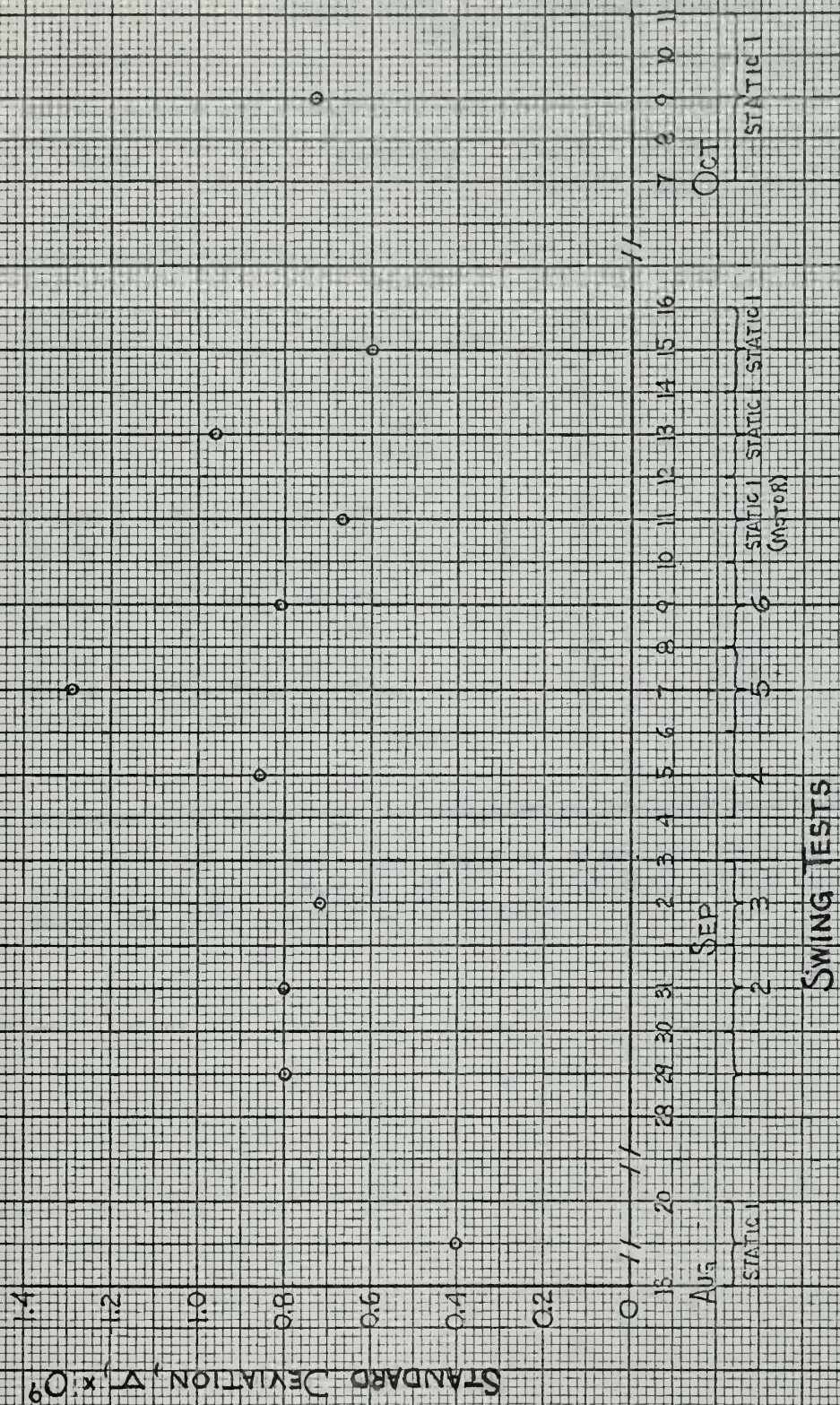


FIGURE 15

CHANGES IN STABILITY OF
WESTERN ELECTRIC 0-76A/u
DURING SWING TESTS

TABLE VI
TEST RESULTS FOR
SULZER MODEL 2.5 FREQUENCY STANDARD
SERIAL NO. 256

Test	Condition	Length (Hours)	Drift Rate $\frac{\Delta f/F}{\text{hour}}$ (pp 10^{11})	Standard Deviation ($\times 10^{11}$)
Static 1	normal	65	2.96	5.04
Static 2	side	49	2.38	6.18
Static 3	upside down	49	2.05	5.41
Static 4	side	48	1.79	4.17
Static 5	front	48	1.68	5.29
Static 6	back	48	1.53	11.35
Static 1	normal	68	1.47	9.30
Swing 1	5 ⁰ , 10 ⁰ , 30 sec.*	49	1.26	7.95
Swing 2	5 ⁰ , 10 ⁰ , 10 sec.	50	1.16	9.40
Swing 3	24 ⁰ , 30 ⁰ , 30 sec.	47	1.04	9.07
Swing 4	24 ⁰ , 30 ⁰ , 10 sec.	47	1.09	6.97
Swing 5	5 ⁰ , 10 ⁰ , 30 sec.	48	0.91	3.91
Swing 6	5 ⁰ , 10 ⁰ , 10 sec.	48	0.98	3.81
Swing 7	24 ⁰ , 30 ⁰ , 30 sec.	48	0.70	4.46
Swing 8	24 ⁰ , 30 ⁰ , 10 sec.	48	0.77	4.83
Static 1	normal	48	0.81	3.76

*5⁰, 10⁰, 30 sec. represents an asymmetric swing of 5⁰ off vertical in one direction and 10⁰ off vertical in the opposite direction with a period of 30 seconds.

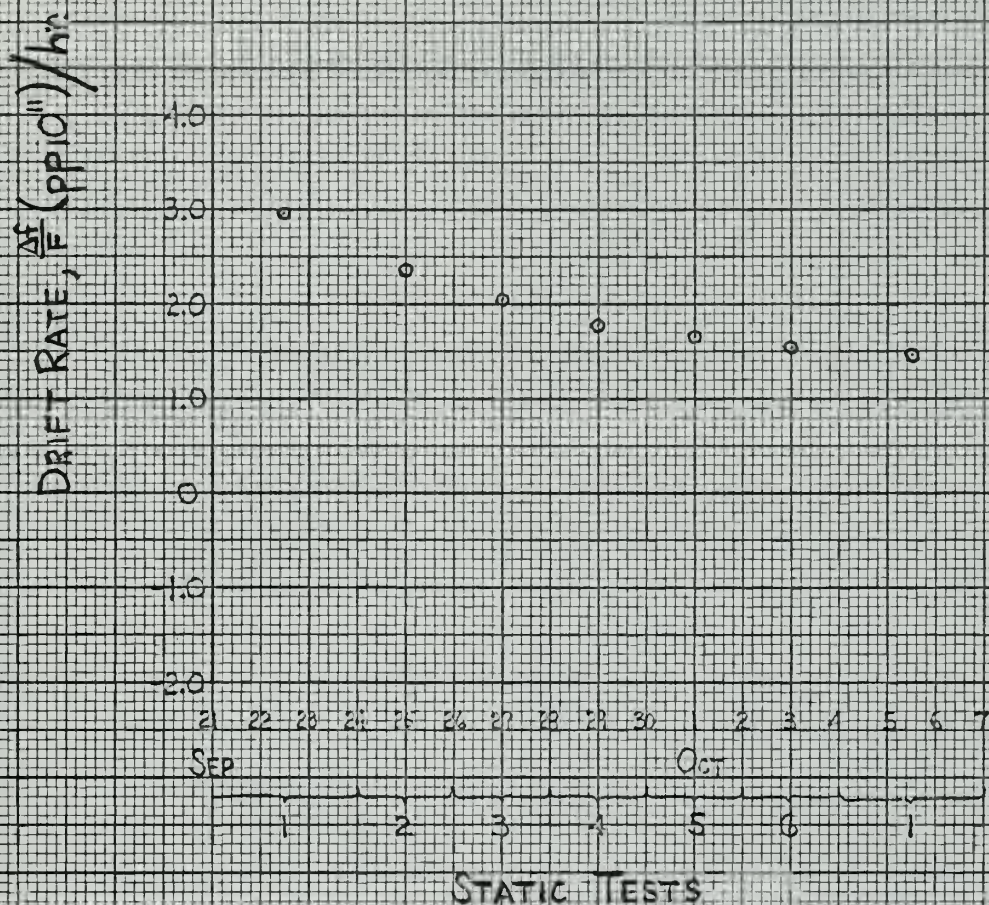


FIGURE 16

CHANGES IN DRIFT RATE
OF SULZER MODEL 2.5
DURING STATIC TESTS

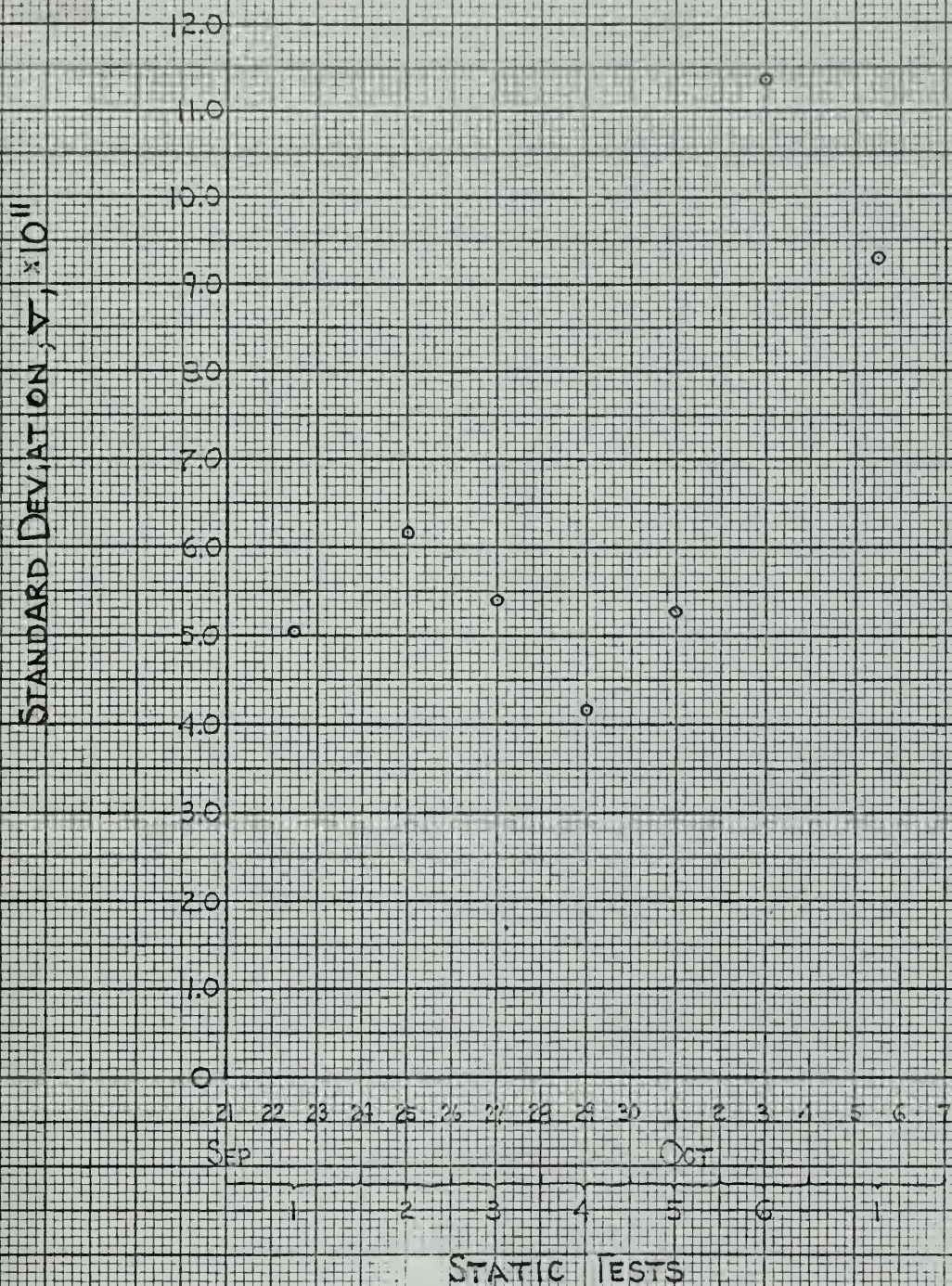


FIGURE 17

CHANGES IN STABILITY
OF SULZER MODEL 2.5
DURING STATIC TESTS



FIGURE 18
CHANGES IN DRIIFT RATE
OF SULZER MODEL 2.5
DURING SWING TESTS

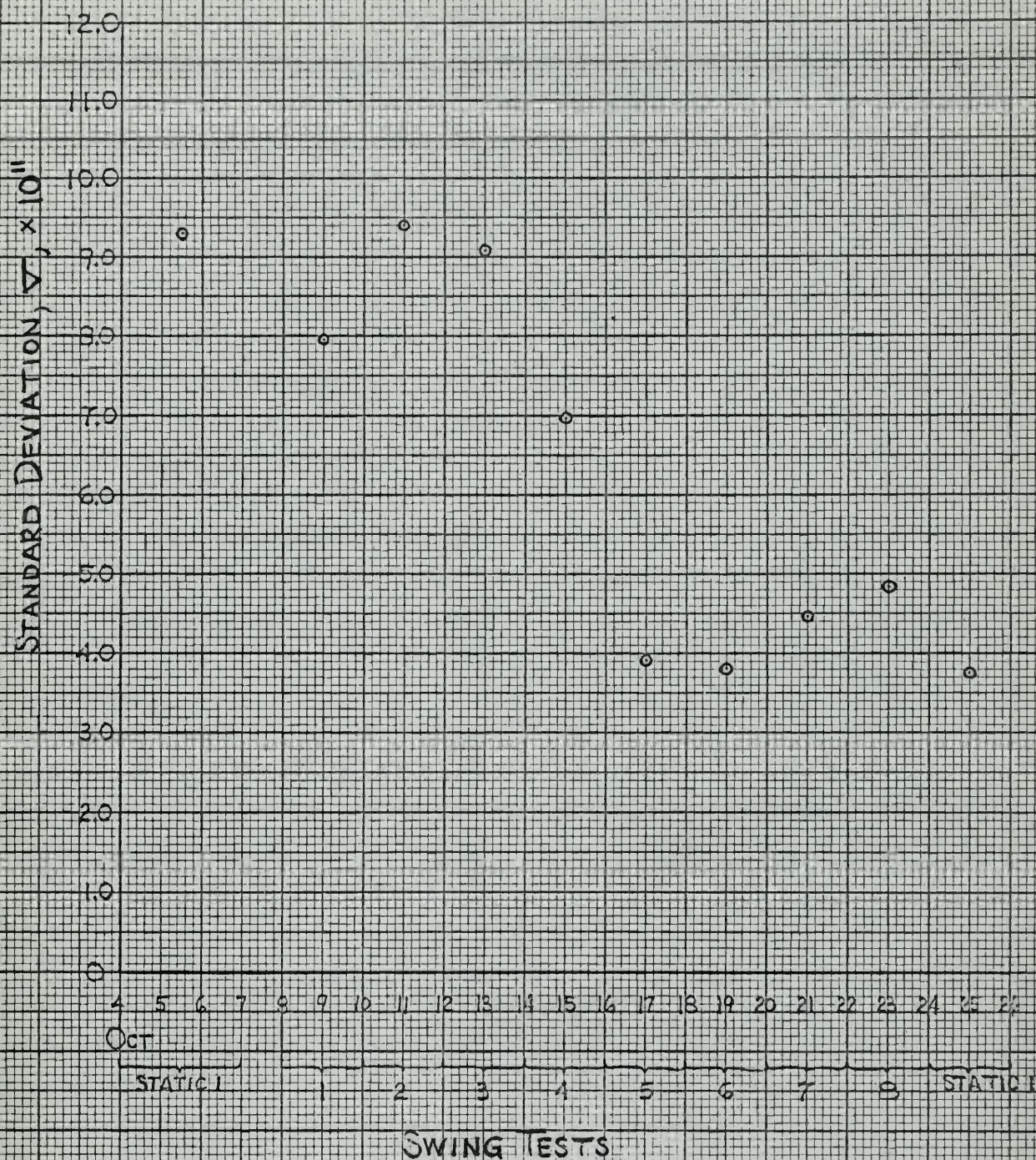


FIGURE 19

CHANGES IN STABILITY
OF SULZER MODEL 2.5
DURING SWING TESTS



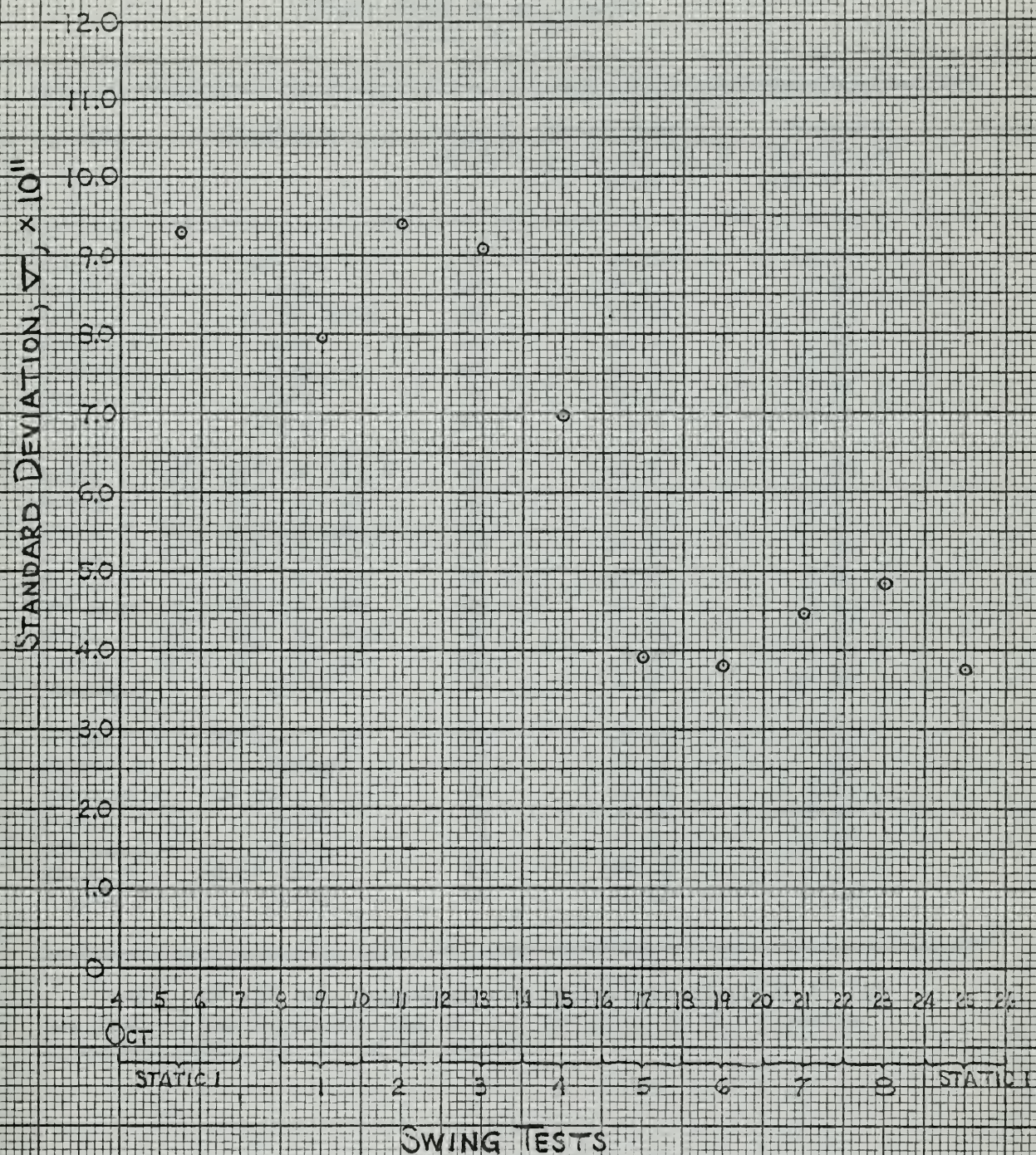


FIGURE 19

CHANGES IN STABILITY
OF SULZER MODEL 2.5
DURING SWING TESTS

TABLE VII

TEST RESULTS FOR
SULZER MODEL D5 OSCILLATOR
SERIAL NO. 25

Test	Condition	Length (hours)	Drift Rate $\frac{\Delta f}{F}$ (pp 10^{11}) hour	Standard Deviation ($\times 10^{11}$)
Static 1	normal	65	-4.14	8.46
Static 2	side	49	-3.61	7.28
Static 3	upside down	49	-3.13	6.17
Static 4	side	48	-2.81	7.10
Static 5	front	48	-2.51	5.93
Static 6	back	48	-2.26	8.22
Static 1	normal	68	-2.31	5.66
Swing 1	5°, 10°, 30 sec.*	49	-2.73	15.06
Swing 2	5°, 10°, 10 sec.	50	-2.25	12.63
Swing 3	24°, 30°, 30 sec.	47	-1.90	12.63
Swing 4	24°, 30°, 10 sec.	47	-1.47	4.28
Swing 5	5°, 10°, 30 sec.	48	-1.41	6.64
Swing 6	5°, 10°, 10 sec.	48	-1.42	9.28
Swing 7	24°, 30°, 30 sec.	48	-1.61	11.23
Swing 8	24°, 30°, 10 sec.	48	-0.68	9.30
Static 1	normal	48	-0.81	10.22
Vibrate 1	20 cps, 1 g	12	-5.02	3.92
Static 1	normal	12	-3.59	7.26
Vibrate 2	20 cps, 1 g	10	-2.42	9.64
Static 1	normal	18	-3.01	8.45
Static 1	normal	17	-1.01	7.99
Shock 1	0.3" fall	12	+0.71	9.11
Static 1	normal	60	-1.63	4.89

*5°, 10°, 30 sec. represents an asymmetric swing of 5° off vertical in one direction and 10° off vertical in the opposite direction with a period of 30 seconds.

THE
 NATIONAL BUREAU OF STANDARDS
 OF THE UNITED STATES DEPARTMENT OF COMMERCE
 OFFICE OF THE CHIEF OF BUREAU

Standard Weight No.	Weight in Grams	Weight in Pounds	Weight in Ounces	Weight in Grains
1	1000	2.20462	16.0134	154.323
2	500	1.10231	8.00672	77.1615
5	500	1.10231	8.00672	77.1615
10	1000	2.20462	16.0134	154.323
20	2000	4.40924	32.0268	308.646
50	5000	11.0231	80.0672	771.615
100	10000	22.0462	160.134	1543.23
250	25000	55.1155	400.336	3858.08
500	50000	110.231	800.672	7716.15
1000	100000	220.462	1601.34	15432.3
2000	200000	440.924	3202.68	30864.6
5000	500000	1102.31	8006.72	77161.5
10000	1000000	2204.62	16013.4	154323
25000	2500000	5511.55	40033.6	385808
50000	5000000	11023.1	80067.2	771615
100000	10000000	22046.2	160134	1543230
250000	25000000	55115.5	400336	3858080
500000	50000000	110231	800672	7716150
1000000	100000000	220462	1601340	15432300
2500000	250000000	551155	4003360	38580800
5000000	500000000	1102310	8006720	77161500
10000000	1000000000	2204620	16013400	154323000
25000000	2500000000	5511550	40033600	385808000
50000000	5000000000	11023100	80067200	771615000
100000000	10000000000	22046200	160134000	1543230000
250000000	25000000000	55115500	400336000	3858080000
500000000	50000000000	110231000	800672000	7716150000
1000000000	100000000000	220462000	1601340000	15432300000
2500000000	250000000000	551155000	4003360000	38580800000
5000000000	500000000000	1102310000	8006720000	77161500000
10000000000	1000000000000	2204620000	16013400000	154323000000
25000000000	2500000000000	5511550000	40033600000	385808000000
50000000000	5000000000000	11023100000	80067200000	771615000000
100000000000	10000000000000	22046200000	160134000000	1543230000000
250000000000	25000000000000	55115500000	400336000000	3858080000000
500000000000	50000000000000	110231000000	800672000000	7716150000000
1000000000000	100000000000000	220462000000	1601340000000	15432300000000
2500000000000	250000000000000	551155000000	4003360000000	38580800000000
5000000000000	500000000000000	1102310000000	8006720000000	77161500000000
10000000000000	1000000000000000	2204620000000	16013400000000	154323000000000
25000000000000	2500000000000000	5511550000000	40033600000000	385808000000000
50000000000000	5000000000000000	11023100000000	80067200000000	771615000000000
100000000000000	10000000000000000	22046200000000	160134000000000	1543230000000000
250000000000000	25000000000000000	55115500000000	400336000000000	3858080000000000
500000000000000	50000000000000000	110231000000000	800672000000000	7716150000000000
1000000000000000	100000000000000000	220462000000000	1601340000000000	15432300000000000
2500000000000000	250000000000000000	551155000000000	4003360000000000	38580800000000000
5000000000000000	500000000000000000	1102310000000000	8006720000000000	77161500000000000
10000000000000000	1000000000000000000	2204620000000000	16013400000000000	154323000000000000
25000000000000000	2500000000000000000	5511550000000000	40033600000000000	385808000000000000
50000000000000000	5000000000000000000	11023100000000000	80067200000000000	771615000000000000
100000000000000000	10000000000000000000	22046200000000000	160134000000000000	1543230000000000000
250000000000000000	25000000000000000000	55115500000000000	400336000000000000	3858080000000000000
500000000000000000	50000000000000000000	110231000000000000	800672000000000000	7716150000000000000
1000000000000000000	100000000000000000000	220462000000000000	1601340000000000000	15432300000000000000
2500000000000000000	250000000000000000000	551155000000000000	4003360000000000000	38580800000000000000
5000000000000000000	500000000000000000000	1102310000000000000	8006720000000000000	77161500000000000000
10000000000000000000	1000000000000000000000	2204620000000000000	16013400000000000000	154323000000000000000
25000000000000000000	2500000000000000000000	5511550000000000000	40033600000000000000	385808000000000000000
50000000000000000000	5000000000000000000000	11023100000000000000	80067200000000000000	771615000000000000000
100000000000000000000	10000000000000000000000	22046200000000000000	160134000000000000000	1543230000000000000000
250000000000000000000	25000000000000000000000	55115500000000000000	400336000000000000000	3858080000000000000000
500000000000000000000	50000000000000000000000	110231000000000000000	800672000000000000000	7716150000000000000000
1000000000000000000000	100000000000000000000000	220462000000000000000	1601340000000000000000	15432300000000000000000
2500000000000000000000	250000000000000000000000	551155000000000000000	4003360000000000000000	38580800000000000000000
5000000000000000000000	500000000000000000000000	1102310000000000000000	8006720000000000000000	77161500000000000000000
10000000000000000000000	1000000000000000000000000	2204620000000000000000	16013400000000000000000	154323000000000000000000
25000000000000000000000	2500000000000000000000000	5511550000000000000000	40033600000000000000000	385808000000000000000000
50000000000000000000000	5000000000000000000000000	11023100000000000000000	80067200000000000000000	771615000000000000000000
100000000000000000000000	10000000000000000000000000	22046200000000000000000	160134000000000000000000	1543230000000000000000000
250000000000000000000000	25000000000000000000000000	55115500000000000000000	400336000000000000000000	3858080000000000000000000
500000000000000000000000	50000000000000000000000000	110231000000000000000000	800672000000000000000000	7716150000000000000000000
1000000000000000000000000	100000000000000000000000000	220462000000000000000000	1601340000000000000000000	15432300000000000000000000
2500000000000000000000000	250000000000000000000000000	551155000000000000000000	4003360000000000000000000	38580800000000000000000000
5000000000000000000000000	500000000000000000000000000	1102310000000000000000000	8006720000000000000000000	77161500000000000000000000
10000000000000000000000000	1000000000000000000000000000	2204620000000000000000000	16013400000000000000000000	154323000000000000000000000
25000000000000000000000000	2500000000000000000000000000	5511550000000000000000000	40033600000000000000000000	385808000000000000000000000
50000000000000000000000000	5000000000000000000000000000	11023100000000000000000000	80067200000000000000000000	771615000000000000000000000
100000000000000000000000000	10000000000000000000000000000	22046200000000000000000000	160134000000000000000000000	1543230000000000000000000000
250000000000000000000000000	25000000000000000000000000000	55115500000000000000000000	400336000000000000000000000	3858080000000000000000000000
500000000000000000000000000	50000000000000000000000000000	110231000000000000000000000	800672000000000000000000000	7716150000000000000000000000
1000000000000000000000000000	100000000000000000000000000000	220462000000000000000000000	1601340000000000000000000000	15432300000000000000000000000
2500000000000000000000000000	250000000000000000000000000000	551155000000000000000000000	4003360000000000000000000000	38580800000000000000000000000
5000000000000000000000000000	500000000000000000000000000000	1102310000000000000000000000	8006720000000000000000000000	77161500000000000000000000000
10000000000000000000000000000	1000000000000000000000000000000	2204620000000000000000000000	16013400000000000000000000000	154323000000000000000000000000
25000000000000000000000000000	2500000000000000000000000000000	5511550000000000000000000000	40033600000000000000000000000	385808000000000000000000000000
50000000000000000000000000000	5000000000000000000000000000000	11023100000000000000000000000	80067200000000000000000000000	771615000000000000000000000000
100000000000000000000000000000	10000000000000000000000000000000	220462000000000000000000000000	160134000000000000000000000000	1543230000000000000000000000000
250000000000000000000000000000	25000000000000000000000000000000	551155000000000000000000000000	400336000000000000000000000000	3858080000000000000000000000000
500000000000000000000000000000	50000000000000000000000000000000	1102310000000000000000000000000	800672000000000000000000000000	7716150000000000000000000000000
1000000000000000000000000000000	100000000000000000000000000000000	22046200000000000000000000000000	1601340000000000000000000000000	15432300000000000000000000000000
2500000000000000000000000000000	250000000000000000000000000000000	55115500000000000000000000000000	4003360000000000000000000000000	38580800000000000000000000000000
5000000000000000000000000000000	500000000000000000000000000000000	110231000000000000000000000000000	8006720000000000000000000000000	77161500000000000000000000000000
10000000000000000000000000000000	1000000000000000000000000000000000	2204620000000000000000000000000000	16013400000000000000000000000000	154323000000000000000000000000000
25000000000000000000000000000000	2500000000000000000000000000000000	5511550000000000000000000000000000	40033600000000000000000000000000	385808000000000000000000000000000
50000000000000000000000000000000	5000000000000000000000000000000000	11023100000000000000000000000000000	80067200000000000000000000000000	771615000000000000000000000000000
100000000000000000000000000000000	10000000000000000000000000000000000	220462000000000000000000000000000000	160134000000000000000000000000000	1543230000000000000000000000000000
250000000000000000000000000000000	250000000000000000000000000000000000	551155000000000000000000000000000000	4003360000000000000000000000000000	3858080000000000000000000000000000
500000000000000000000000000000000	5000000000000000000000000000000000000	1102310000000000000000000000000000000	8006720000000000000000000000000000	7716150000000000000000000000000000
1000000000000000000000000000000000	10000000000000000000000000000000000000	22046200000000000000000000000000000000	16013400000000000000000000000000000	15432300000

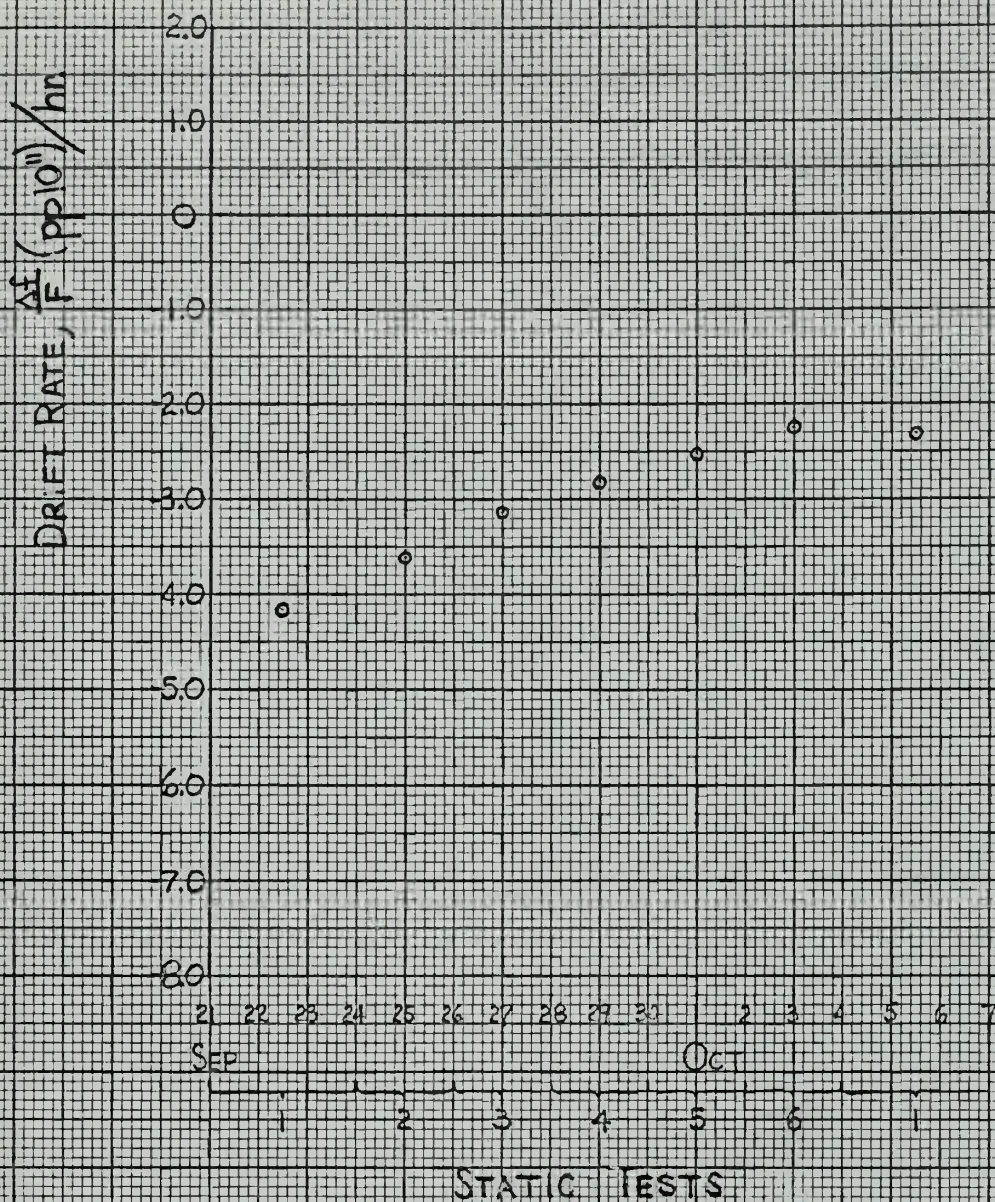


FIGURE 20

CHANGES IN DRIFT RATE
OF SULZER MODEL D5
SERIAL NO. 25
DURING STATIC TESTS

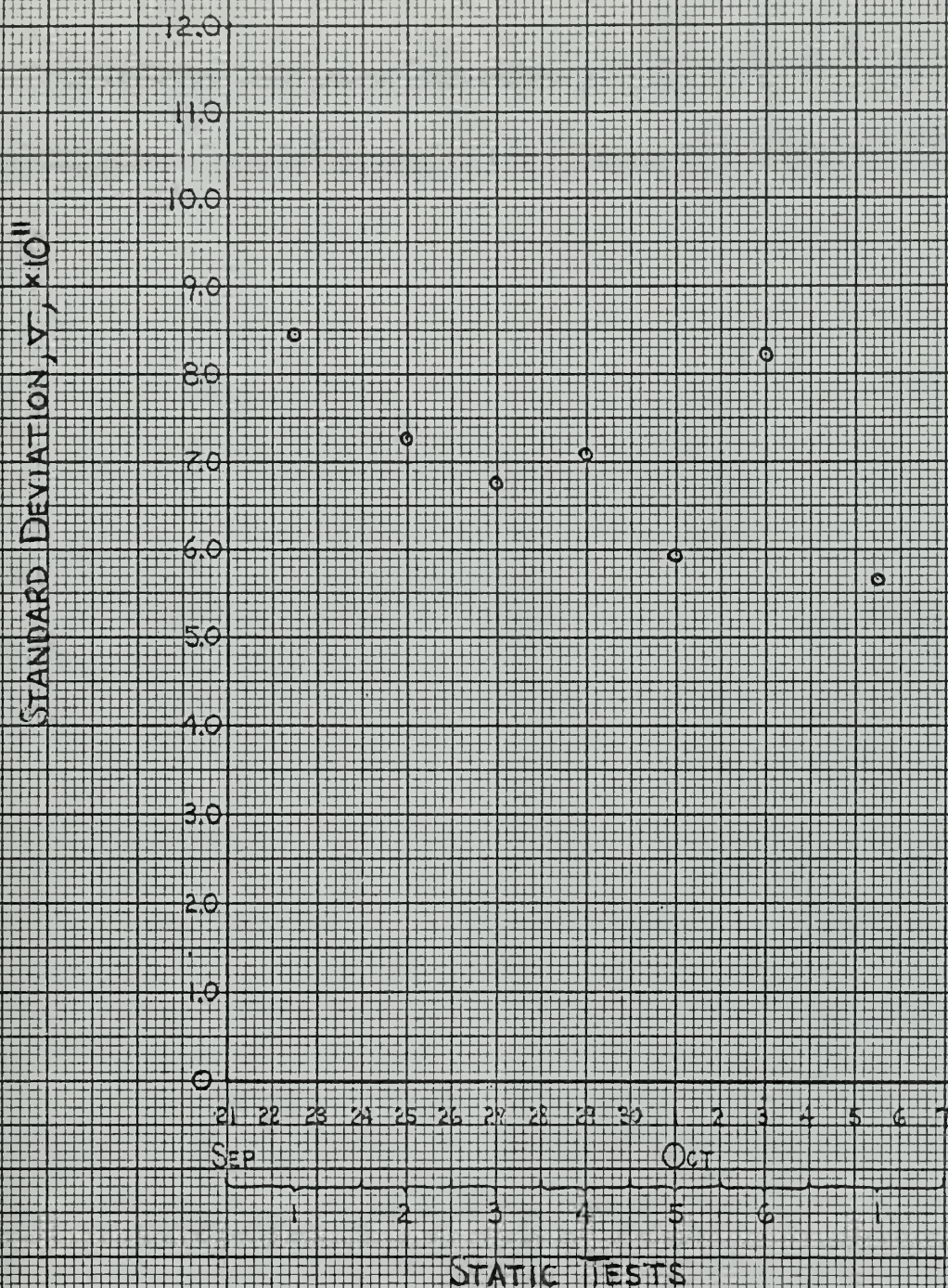


FIGURE 21

CHANGES IN STABILITY
OF SULZER MODEL D5
SERIAL NO. 25
DURING STATIC TESTS



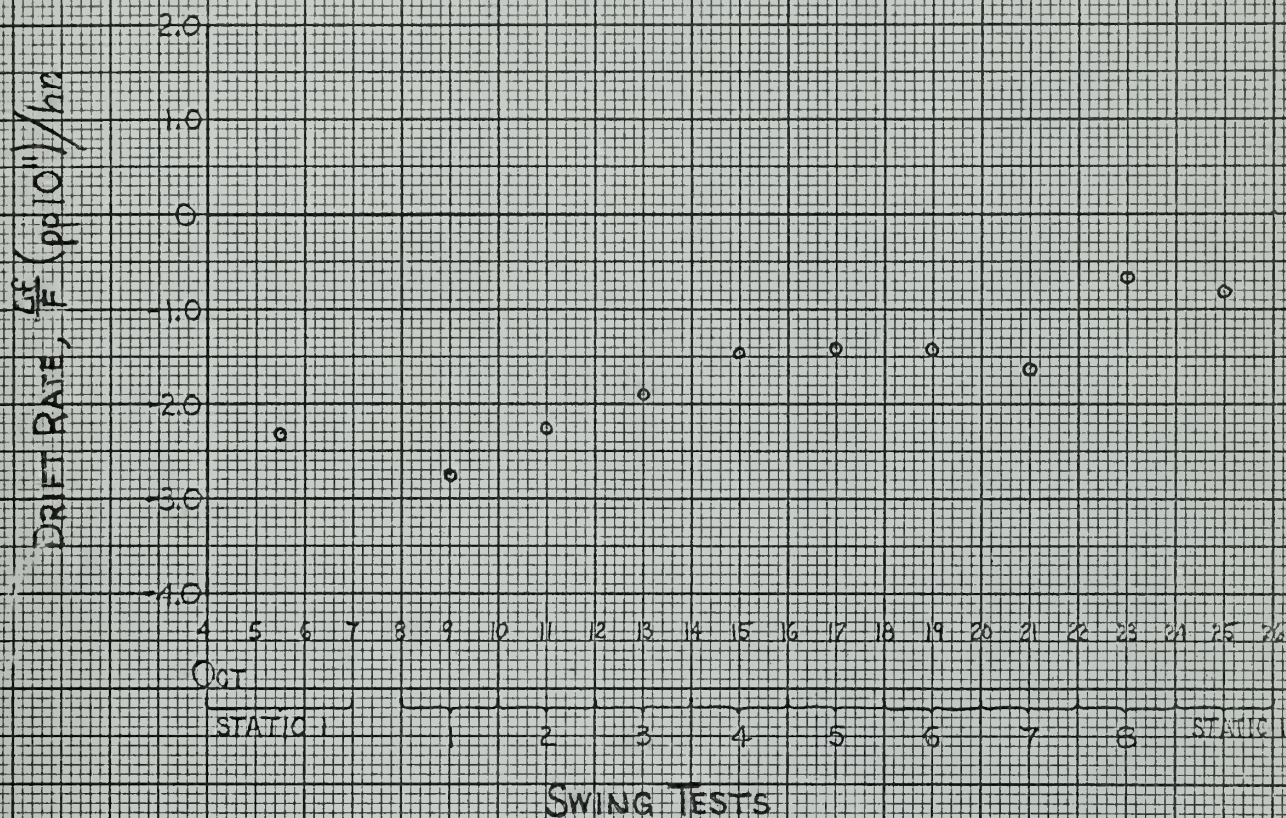
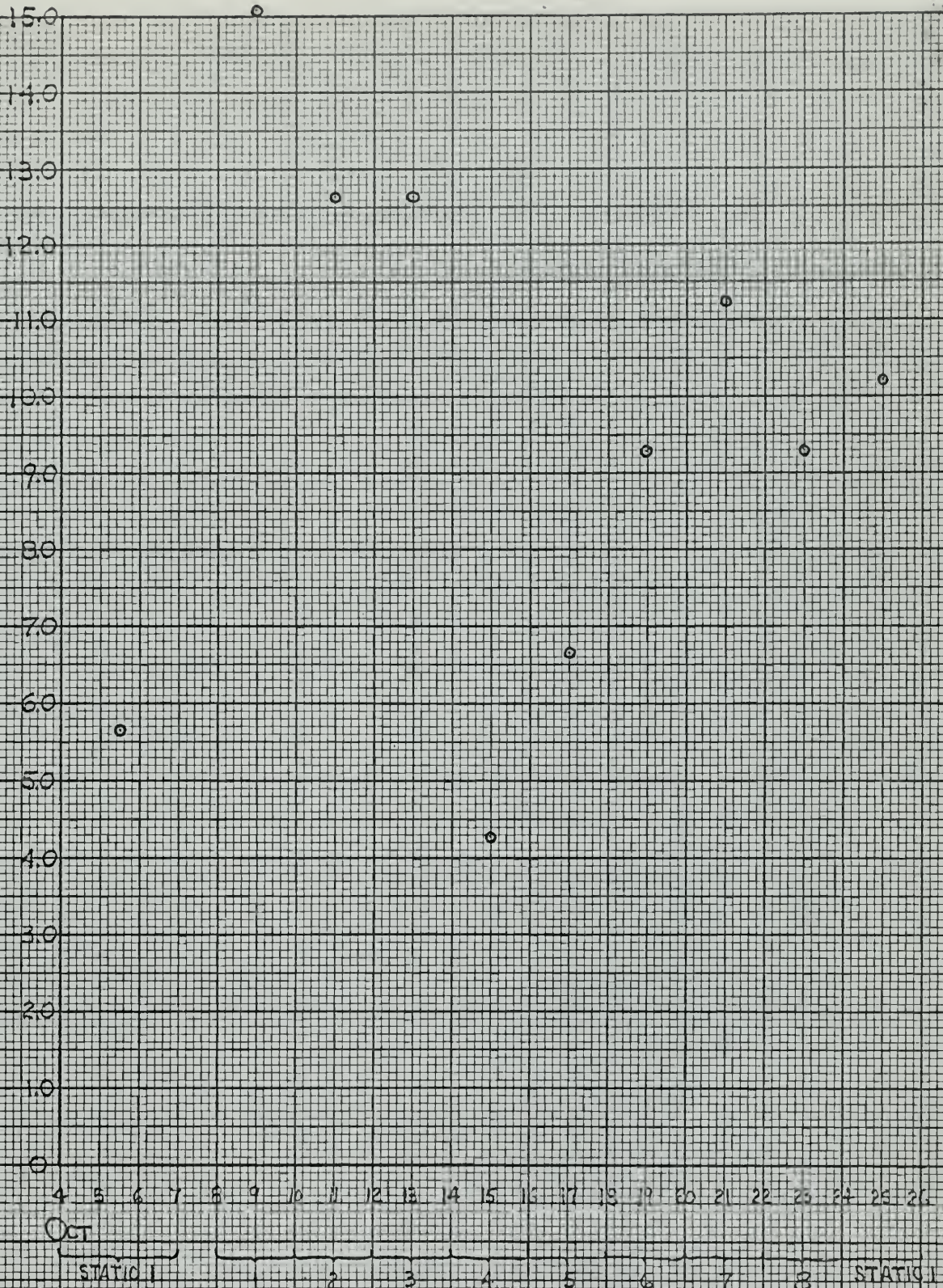


FIGURE 22

CHANGES IN DRIFT RATE
OF SULZER MODEL D5
SERIAL NO. 25
DURING SWING TESTS

STANDARD DEVIATION, σ , x 10"



SWING TESTS

FIGURE 23

CHANGES IN STABILITY
OF SULZER MODEL D5
SERIAL NO. 25
DURING SWING TESTS



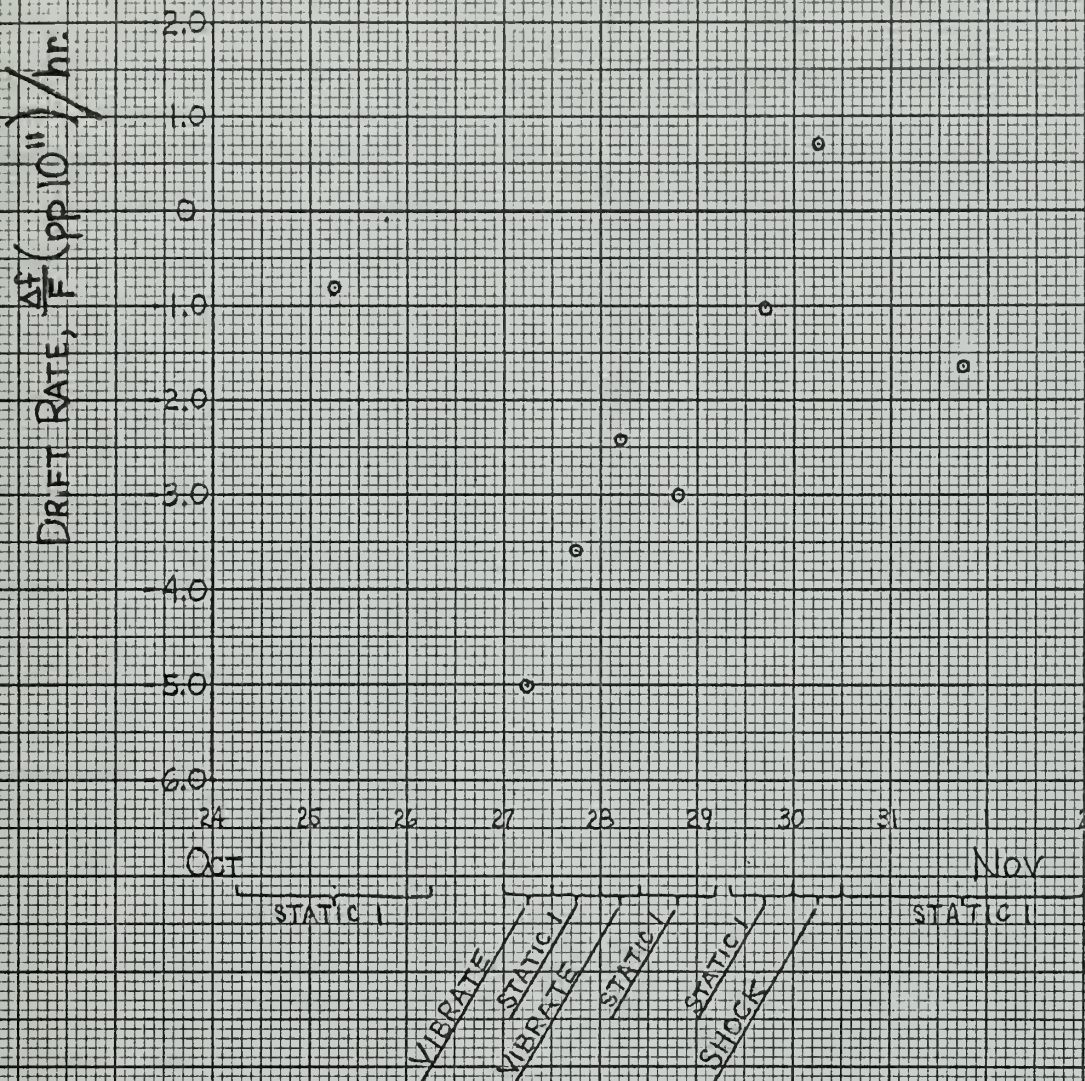


FIGURE 24

CHANGES IN DRIFT RATE OF
SULZER MODEL D5, SERIAL NO. 25
DURING VIBRATION AND SHOCK TESTS



STANDARD DEVIATION σ , $\times 10^{11}$

14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0

24 25 26 27 28 29 30 31 2

Oct

Nov

STATIC

VIBRATE
STATIC
VIBRATE
STATIC

STATIC
SHOCK

STATIC

FIGURE 25

CHANGES IN STABILITY OF
SULZER MODEL D5, SERIAL NO. 25
DURING VIBRATION AND SHOCK TESTS



TABLE VIII

TEST RESULTS FOR
SULZER MODEL D5 OSCILLATOR
SERIAL NO. 19

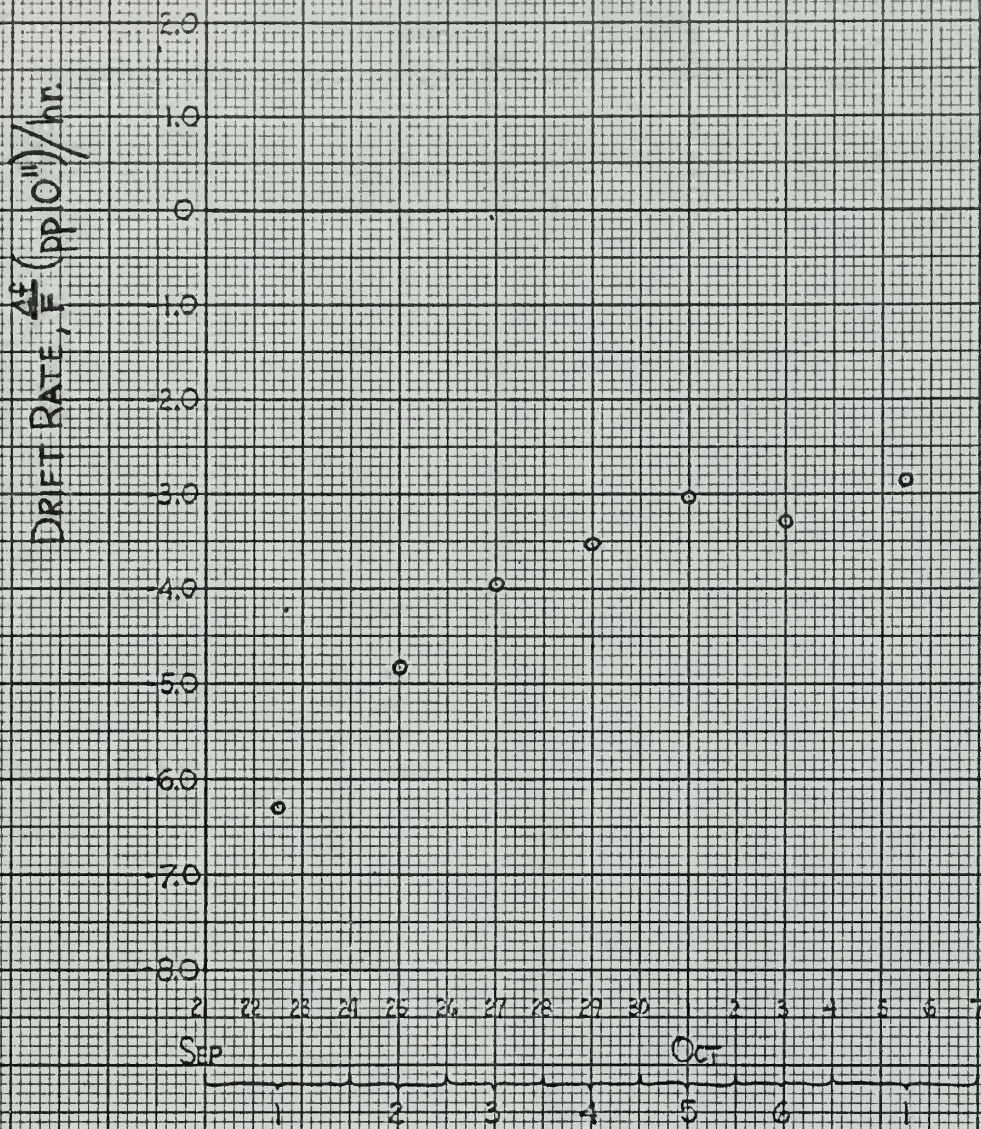
Test	Condition	Length (hours)	Drift Rate $\frac{\Delta f/F}{\text{hour}}$ ($\text{pp } 10^{11}$)	Standard Deviation ($\times 10^{11}$)
Static 1	normal	65	-6.29	8.46
Static 2	side	49	-4.82	8.33
Static 3	upside down	49	-3.96	8.36
Static 4	side	48	-3.52	8.32
Static 5	front	48	-3.02	8.86
Static 6	back	48	-3.28	8.98
Static 1	normal	68	-2.86	6.32
Swing 1	5°, 10°, 30 sec.*	49	-3.31	8.75
Swing 2	5°, 10°, 10 sec.	50	-2.68	7.68
Swing 3	24°, 30°, 30 sec.	47	-2.46	4.74
Swing 4	24°, 30°, 10 sec.	47	-2.22	4.12
Swing 5	5°, 10°, 30 sec.	48	-2.03	6.06
Swing 6	5°, 10°, 10 sec.	48	-2.12	4.67
Swing 7	24°, 30°, 30 sec.	48	-2.12	5.88
Swing 8	24°, 30°, 10 sec.	48	-1.77	9.96
Static 1	normal	48	-1.64	8.22
Vibrate 1	20 cps, 1 g	12	-4.63	9.55
Static 1	normal	12	-3.11	4.25
Vibrate 2	20 cps, 1 g	10	-3.81	5.10
Static 1	normal	18	-3.03	9.52
Static 1	normal	17	-1.69	5.86
Shock 1	0.3" fall	12	-2.36	8.45
Static 1	normal	60	-2.19	10.06

*5°, 10°, 30 sec. represents an asymmetric swing of 5° off vertical in one direction and 10° off vertical in the opposite direction with a period of 30 seconds.

THE ANNUAL REPORT OF THE COMMISSIONER OF THE LAND OFFICE FOR THE YEAR 1887

REVENUE				
Item	1886	1887	1888	1889
Land Sales	1,234,567	1,345,678	1,456,789	1,567,890
Mineral Rights	567,890	678,901	789,012	890,123
Water Rights	345,678	456,789	567,890	678,901
Timber Rights	234,567	345,678	456,789	567,890
Other	123,456	234,567	345,678	456,789
Total	2,496,108	2,661,013	2,815,158	2,961,593
EXPENDITURES				
Item	1886	1887	1888	1889
Salaries	123,456	134,567	145,678	156,789
Travel	45,678	56,789	67,890	78,901
Printing	34,567	45,678	56,789	67,890
Repairs	23,456	34,567	45,678	56,789
Other	12,345	23,456	34,567	45,678
Total	239,502	294,057	345,678	396,247

THE COMMISSIONER OF THE LAND OFFICE
 HAS THE HONOR TO ACKNOWLEDGE THE RECEIPT OF THE
 ABOVE SUMS OF MONEY FROM THE TREASURY OF THE UNITED STATES



STATIC TESTS

FIGURE 26

CHANGES IN DRIFT RATE
OF SULZER MODEL D5
SERIAL NO. 19
DURING STATIC TESTS



STANDARD DEVIATION, σ , $\times 10^4$

12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0

21 22 23 24 25 26 27 28 29 30 1 2 3 4 5 6 7
SEP OCT
1 2 3 4 5 6 7

STATIC TESTS

FIGURE 27

CHANGES IN STABILITY
OF SULZER MODEL D5
SERIAL NO. 19
DURING STATIC TESTS



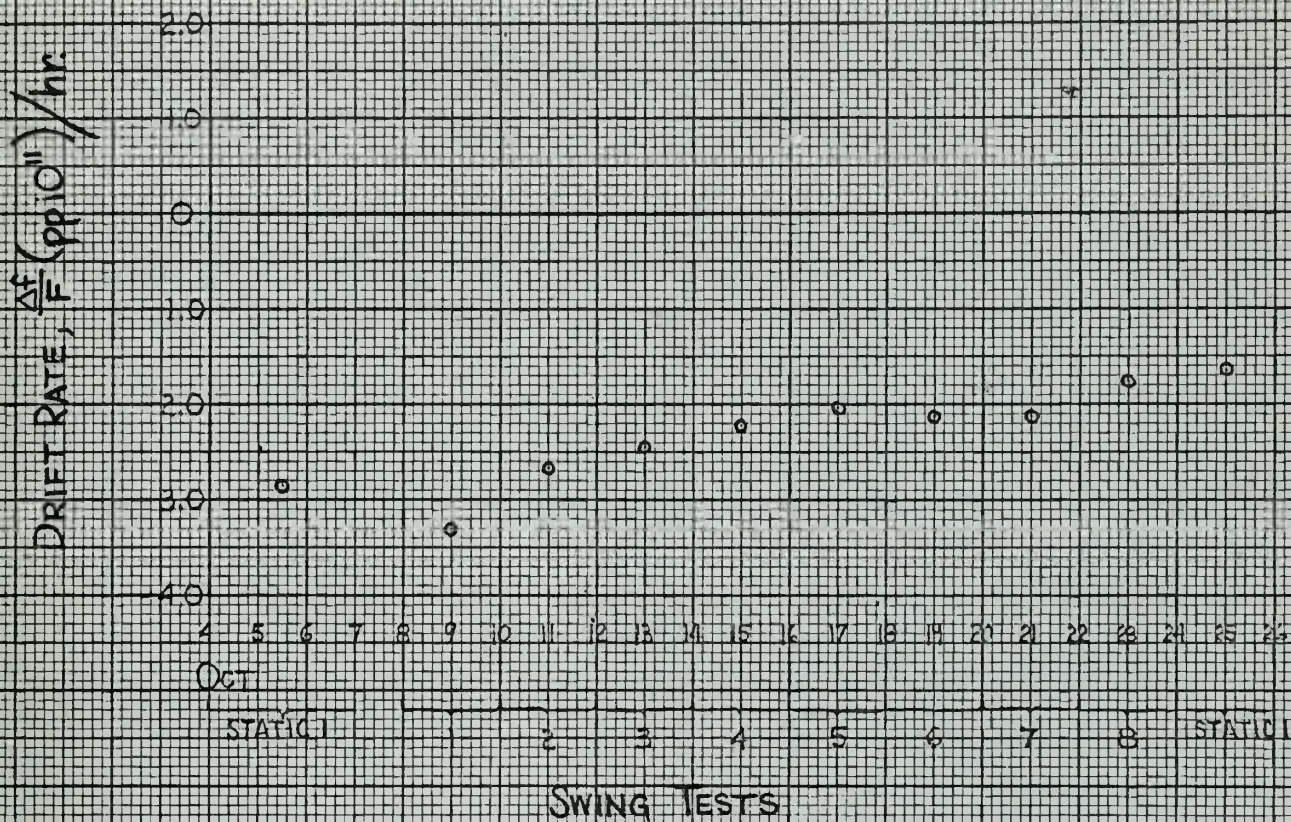
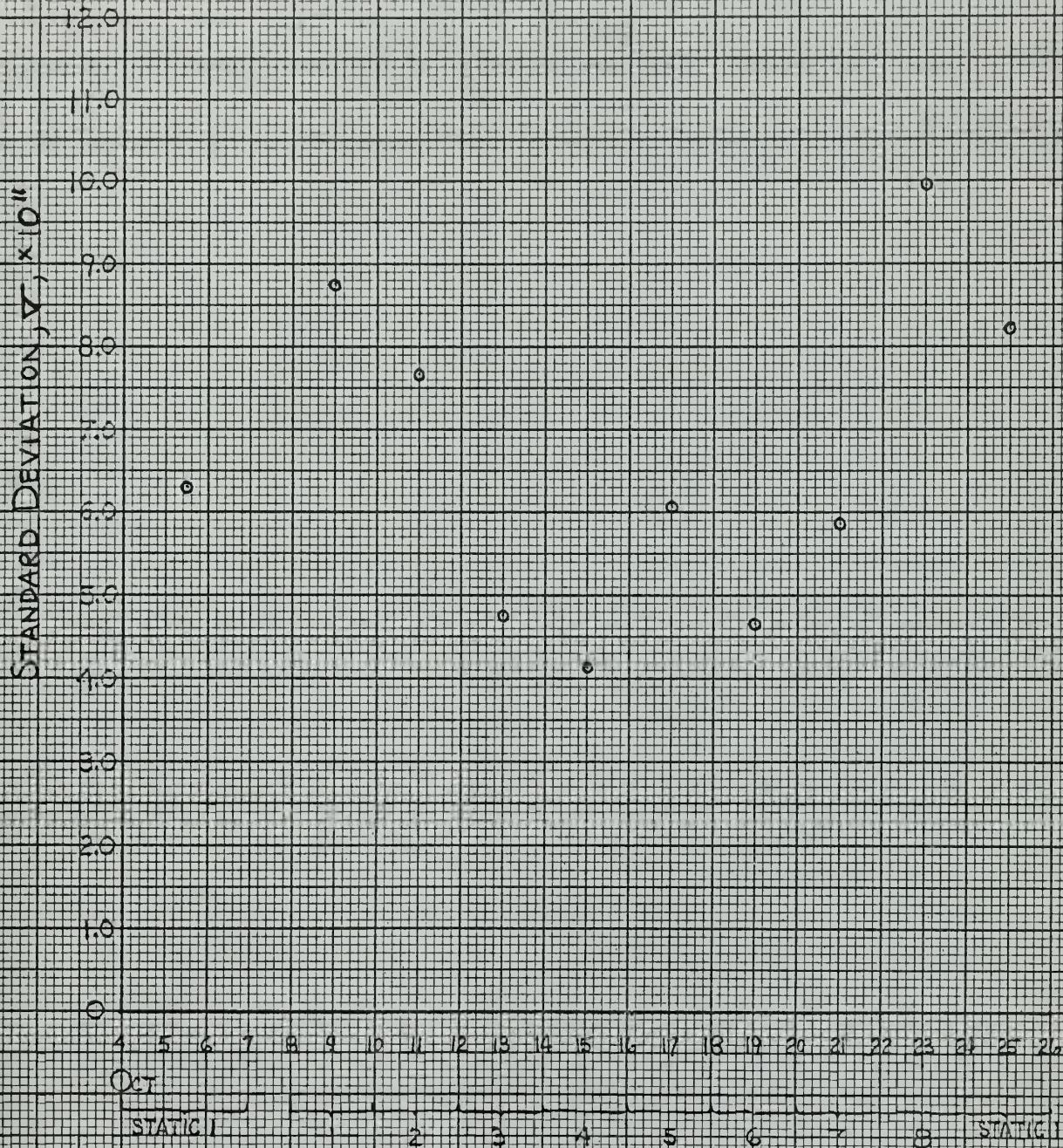


FIGURE 28

CHANGES IN DRIFT RATE
OF SULZER MODEL D5
SERIAL NO. 19
DURING SWING TESTS





SWING TESTS

FIGURE 29

CHANGES IN STABILITY
OF SULZER MODEL D5
SERIAL NO. 19
DURING SWING TESTS



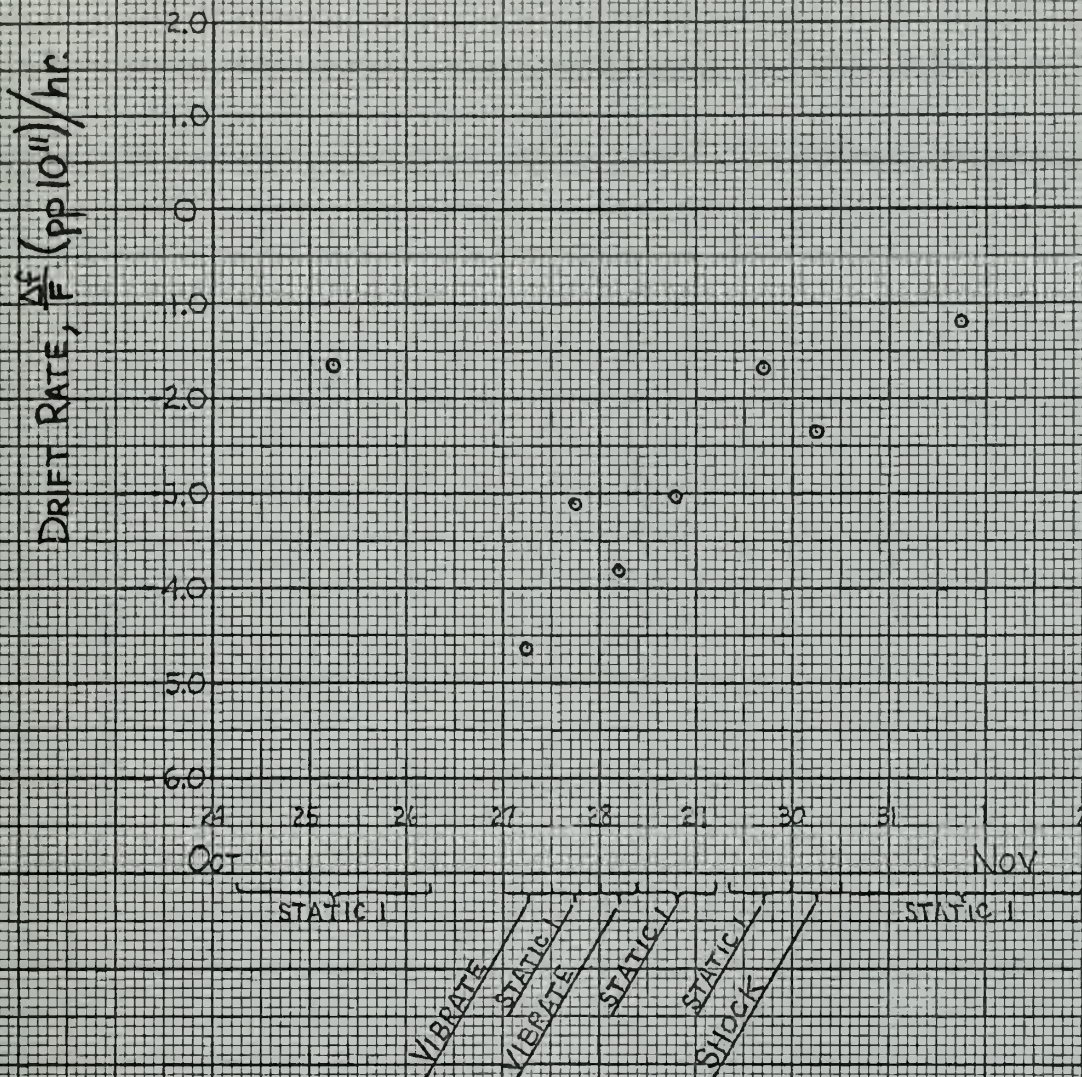


FIGURE 30

CHANGES IN DRIFT RATE OF
SULZER MODEL D5, SERIAL NO. 19
DURING VIBRATION AND SHOCK TESTS



STANDARD DEVIATION, σ , $\times 10^{11}$

14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0

24 25 26 27 28 29 30 31 2
OCT NOV

STATIC 1

VIBRATE

STATIC 1

VIBRATE

STATIC 1

SHOCK

STATIC 1

FIGURE 31

CHANGES IN STABILITY OF
SULZER MODEL D5, SERIAL NO. 19
DURING VIBRATION AND SHOCK TESTS



TABLE IX
TEST RESULTS FOR
SULZER MODEL D5 OSCILLATOR
SERIAL NO. 22

Test	Condition	Length (hours)	Drift Rate $\frac{\Delta f/F}{\text{hour}}$ (pp 10 ¹¹)	Standard Deviation (x 10 ¹¹)
Static 1	normal	65	-6.68	4.97
Static 2	side	49	-5.14	7.44
Static 3	upside down	49	-4.31	6.31
Static 4	side	48	-4.26	10.12
Static 5	front	48	-2.90	9.77
Static 6	back	48	-2.64	7.67
Static 1	normal	68	-2.26	8.64
Swing 1	5°, 10°, 30 sec. *	49	-2.41	7.85
Swing 2	5°, 10°, 10 sec.	50	-2.10	5.20
Swing 3	24°, 30°, 30 sec.	47	-1.76	4.09
Swing 4	24°, 30°, 10 sec.	47	-1.54	4.08
Swing 5	5°, 10°, 30 sec.	48	-1.42	4.47
Swing 6	5°, 10°, 10 sec.	48	-1.32	3.07
Swing 7	24°, 30°, 30 sec.	48	-1.39	3.09
Swing 8	24°, 30°, 10 sec.	48	-1.08	4.65
Static 1	normal	48	-0.95	5.00
Vibrate 1	20 cps, 1 g	12	-4.50	7.46
Static 1	normal	12	-2.74	2.18
Vibrate 2	20 cps, 1 g	10	-2.80	2.56
Static 1	normal	18	-1.99	4.26
Static 1	normal	17	-0.55	3.32
Shock 1	0.3" fall	12	-0.02	7.39
Static 1	normal	60	-1.14	4.37

*5°, 10°, 30 sec. represents an asymmetric swing of 5° off vertical in one direction and 10° off vertical in the opposite direction with a period of 30 seconds.

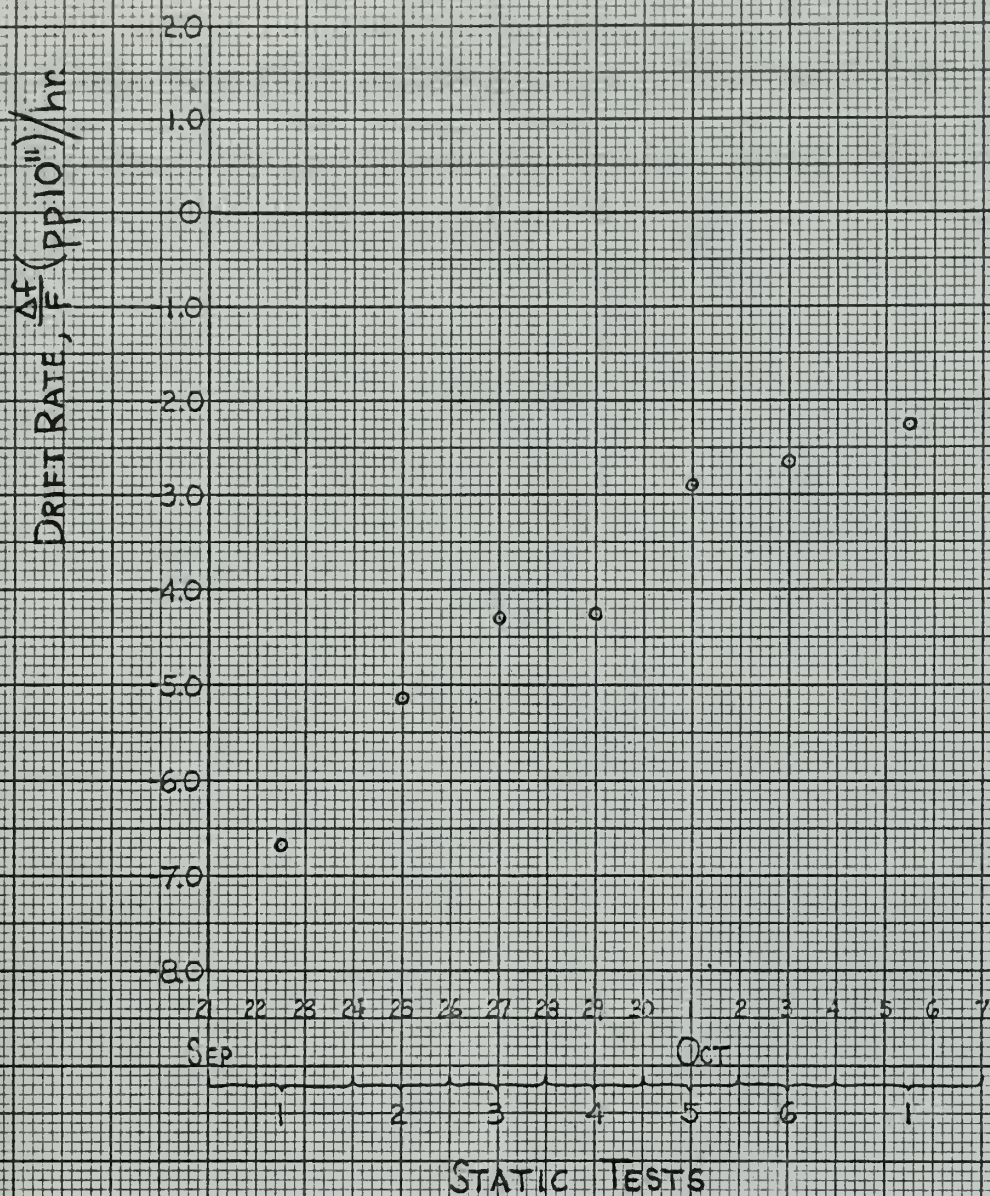
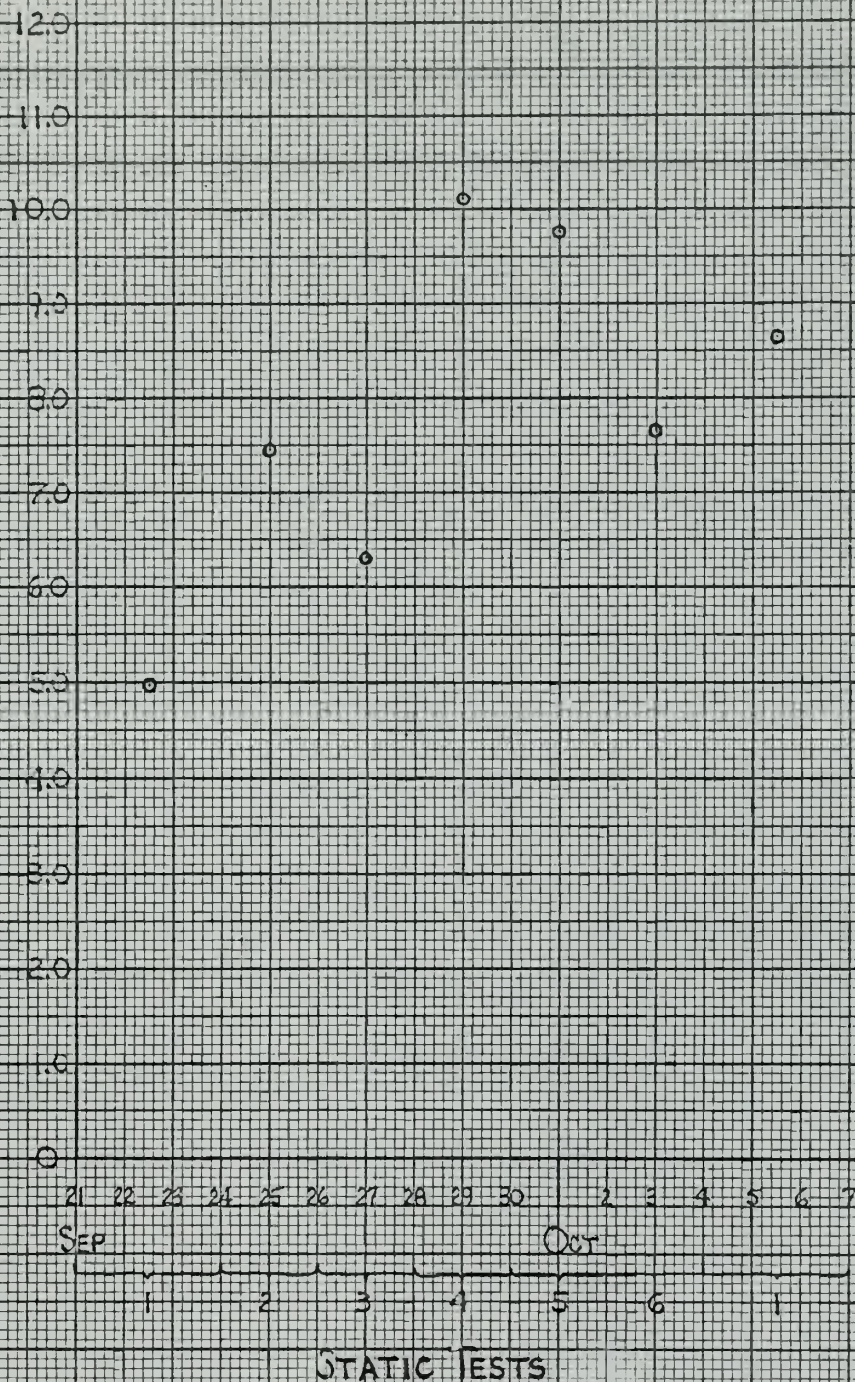


FIGURE 32
CHANGES IN DRIFT RATE
OF SULZER MODEL D5
SERIAL NO. 22
DURING STATIC TESTS

STANDARD DEVIATION, σ , $\times 10''$



STATIC TESTS

FIGURE 33

CHANGES IN STABILITY
OF SULZER MODEL D5
SERIAL NO. 22
DURING STATIC TESTS

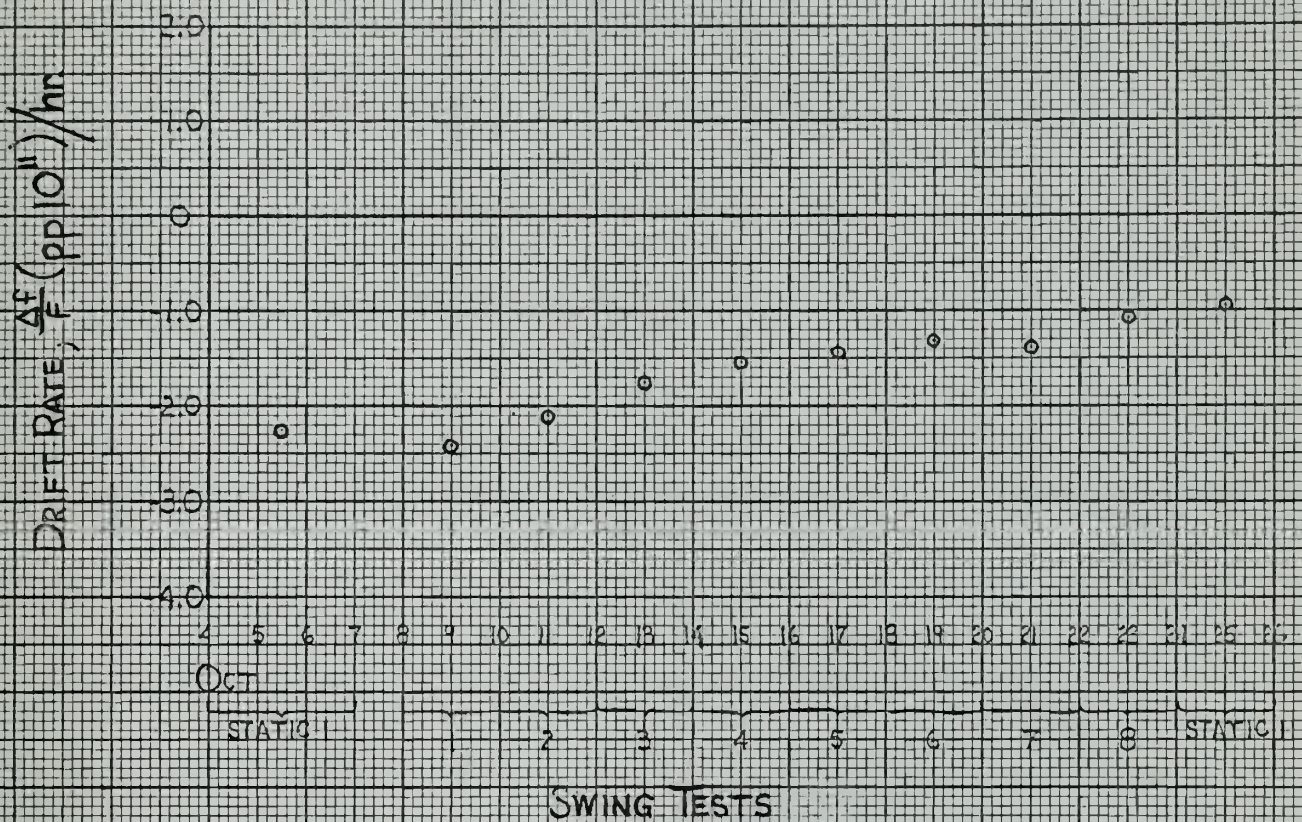


FIGURE 34

CHANGES IN DRIFT RATE
OF SULZER MODEL D5
SERIAL NO. 22
DURING SWING TESTS

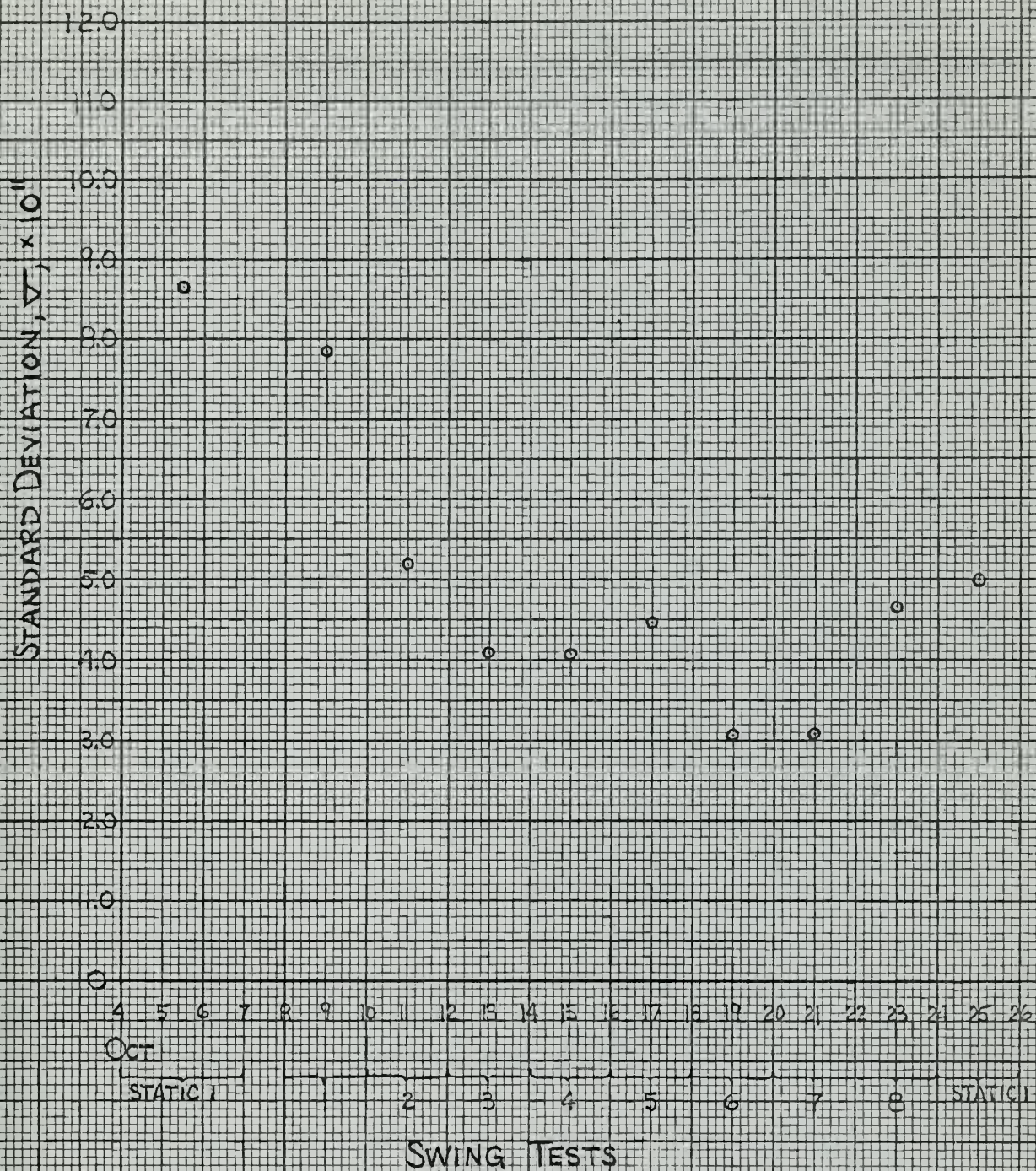


FIGURE 35
CHANGES IN STABILITY
OF SULZER MODEL D5
SERIAL NO. 22
DURING SWING TESTS

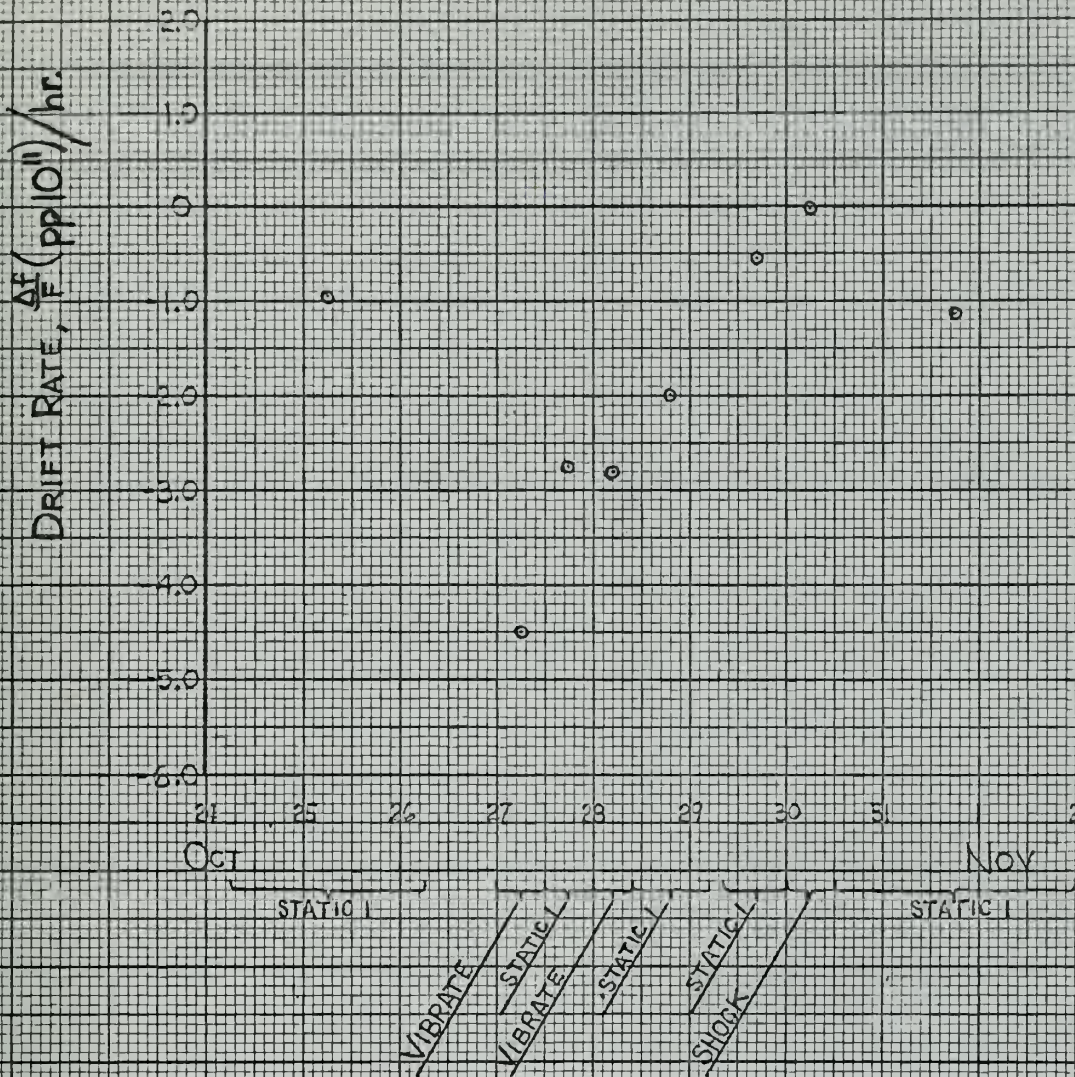


FIGURE 36

CHANGES IN DRIFT RATE OF
SULZER MODEL D5, SERIAL NO. 22
DURING VIBRATION AND SHOCK TESTS



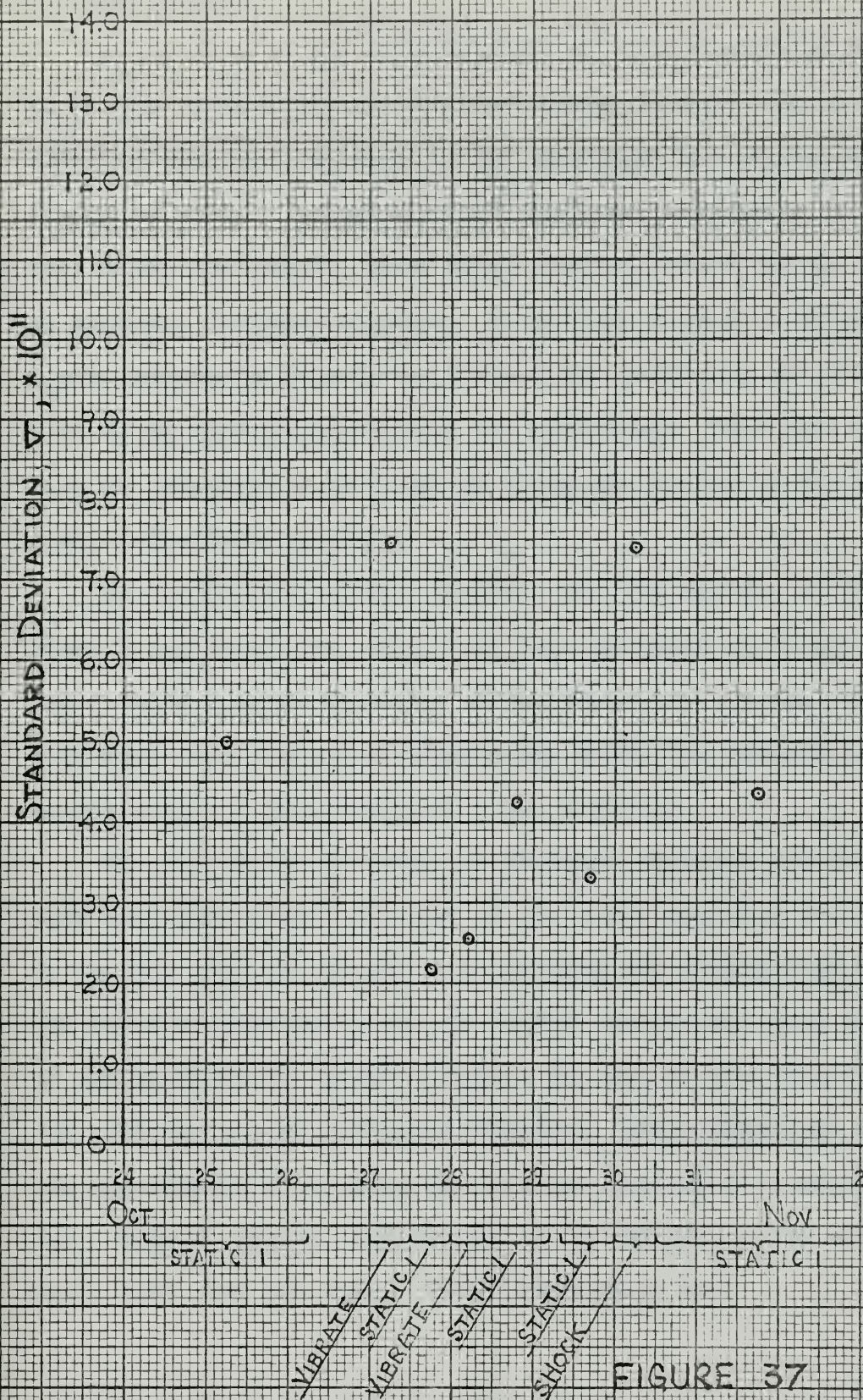


FIGURE 37

CHANGES IN STABILITY OF
SULZER MODEL D5, SERIAL NO. 22
DURING VIBRATION AND SHOCK TESTS



6. Observations.

At the onset of the investigation, the investigator had hoped to be able to correlate any observed changes in drift rate or frequency stability with the conditions of the particular test during which the change was noted. A seemingly ideal situation was present with the four Sulzer oscillators, three being identical models and the fourth an excellent frequency standard. It had been planned to obtain additional information from Sulzer Laboratories concerning the orientation of the crystal plane within the oscillators. With this information the investigator had hoped to relate the results of the static tests with crystal position.

The manufacturer stated, however, that the position of the crystal plane is not fixed, but varies with each individual oscillator. Since the only remaining method of determining the crystal orientation would have required disturbing the double-oven assemblies, this second aspect of the investigation was abandoned.

The correlation of changes in frequency stability and drift rates with test conditions in the case of the Sulzer equipment was hampered by the fact that the limited time available for testing required that the tests be conducted during the initial warm-up and aging period of the oscillators. As the equipment was new, no data record was available for use as a behavior reference. These conditions prevented the investigator from making the detailed conclusions originally hoped for. Instead, general observations of the behavior of the oscillators while under test were made. These observations are:

Western Electric Frequency Standard 0-76A/U

Static Tests. Drift rates varied between $0.04 \text{ (pp } 10^9 \text{) per hour}$ and $1.49 \text{ (pp } 10^9 \text{) per hour}$, with the lowest value occurring while the oscillator was in the normal position. However, each time the oscillator was in this position, a different drift rate was observed (0.11, 0.10, 0.04). During a portion of the Static Five Test with the oscillator tipped forward on its face the drift rate was $0.05 \text{ (pp } 10^9 \text{)}/\text{hr.}$

Stability (standard deviation) varied from 0.35×10^{-9} to 1.12×10^{-9} with the lowest value occurring while the unit was in a normal position. However, as in the case of the drift rates, each time the oscillator was returned to its normal position, a different value was observed (0.35, 0.32, 0.57). Once again there were instances where the stability while the oscillator was in some position other than normal was better than that observed for some of the normal position test periods.

The maximum values of drift rate and standard deviation occurred during the recovery periods as discussed in Section 5.

Swing Tests. The drift rate was certainly affected by the swinging motion although during the test period from 12 to 14 September while the oscillator was in the Static One position the drift rate was almost as great as the largest observed during swinging. The rates varied from $0.133 \text{ (pp } 10^9 \text{)}/\text{hr.}$ to $-0.037 \text{ (pp } 10^9 \text{)}/\text{hr.}$

Published by the American Medical Association, 535 North Dearborn Street, Chicago, Ill.
Subscription price, Five Dollars per Annum in Advance. Single Copies, Fifteen Cents.
Entered as Second-Class Matter, May 26, 1912, Post Office at Chicago, Ill., under
Post Office No. 363, with change of name from "The Medical News" to "The
Journal of the American Medical Association" approved May 26, 1912.
Acceptance for mailing at special rate of postage provided for in Act of
October 3, 1917, authorized May 1, 1918.

Copyright, 1914, by American Medical Association
All rights reserved. No part of this publication may be reproduced without
the written permission of the American Medical Association. Printed and
published by the American Medical Association, 535 North Dearborn Street,
Chicago, Ill. Second-class postage paid at Chicago, Ill., and at additional
mailing offices. Postmaster: Please send address changes in advance.
This journal is published weekly, except on Sundays and public holidays, when
it is published bi-weekly. The subscription price is in advance and includes
delivery by mail.

Entered as Second-Class Matter, May 26, 1912, Post Office at Chicago, Ill., under
Post Office No. 363, with change of name from "The Medical News" to "The
Journal of the American Medical Association" approved May 26, 1912.

Published by the American Medical Association, 535 North Dearborn Street,
Chicago, Ill. Second-class postage paid at Chicago, Ill., and at additional
mailing offices. Postmaster: Please send address changes in advance.
This journal is published weekly, except on Sundays and public holidays, when
it is published bi-weekly. The subscription price is in advance and includes
delivery by mail.

AMERICAN MEDICAL ASSOCIATION

Values of standard deviation were generally greater during swinging than while at rest, indicating poorer stability under these conditions.

Sulzer Model 2.5 Frequency Standard

Static Tests. The drift rate gradually decreased as the crystal aged and no apparent effects of static position were observed.

Stability varied between 4.2×10^{-11} and 11.4×10^{-11} with the greatest value observed during the Static Six test, while the unit was tipped on its back.

Swing Tests. The drift rate continued to decrease gradually with further aging of the crystal. In three out of four instances, however, the drift rate increased slightly when the swing frequency was increased.

Stability improved as the swing tests progressed, with values of the standard deviation decreasing from 9.3×10^{-11} to 3.8×10^{-11} . In three out of four instances, however, the standard deviation increased when the amplitude of the swing was increased.

Sulzer Model D5 Oscillators

Static Tests. As in the case of the Sulzer frequency standard, the drift rate for each of the three Model D5 oscillators gradually decreased during the aging period.

Stabilities varied between 5×10^{-11} and 10×10^{-11} with no common behavior pattern evident. One oscillator exhibited a downward trend, one an upward trend, and one remained fairly constant.

THE FIRST SECTION OF THE ACT
RELATIVE TO THE REGISTRATION OF
MARRIAGES

SECTION 1.

That all persons who shall be
married in this State, shall be
registered in the office of the
Register of the County in which
the marriage shall be solemnized
and the Register shall keep a
true and correct record of the
same, and shall transmit a
copy of the same to the
Register of the State.

SECTION 2.

That the Register of the County
shall keep a true and correct
record of the marriages
solemnized in his County, and
shall transmit a copy of the
same to the Register of the
State.

SECTION 3.

That the Register of the State
shall keep a true and correct
record of the marriages
solemnized in this State, and
shall transmit a copy of the
same to the Secretary of the
State.

Swing Tests. The drift rates generally decreased during the swinging tests as aging continued.

Stabilities varied from 3×10^{-11} to 15×10^{-11} . The lowest values of standard deviation for each oscillator were obtained during one or another of the swing tests and not during a static period. In three out of four instances when the swing frequency was increased, the stability of various oscillators improved. The exceptional cases, however, did not occur simultaneously.

The stability of two of the oscillators, serial no. 19 and serial no. 22, improved in three out of four instances when the amplitude of the swing was increased.

Vibration and Shock Tests. All drift rates were increased by three or four parts per 10^{11} per hour during the initial vibration test.

Standard deviation varied between 2.2×10^{-11} and 10.1×10^{-11} . All standard deviations were increased during the shock test; the amounts of increase varied from one to four parts per 10^{11} .

In conclusion, the drift rate and frequency stability of the frequency standards were apparently affected to a small degree by swinging motion, although this motion had no definite effect on the Sulzer Model D5 oscillators. The D5 oscillators were affected slightly by shock and vibration. In only a few cases, however, such as the change in stability during the shock test, or the change in drift rate during the initial vibration test, did all three Model D5

oscillators respond in a similar manner. Generally, opposite reactions occurred, i.e., during a given test period, drift rates of two oscillators would increase while the third decreased, or the stabilities of a different pair of oscillators would decrease while the third increased or remained constant.

In spite of the lack of positive correlation of changes in drift rate and stability with conditions of position and motion, the results of the investigation were fruitful in that they indicated a lack of vulnerability of the oscillator units to motion in general.

7. Recommendations for further study.

Since the initial warm-up and aging period of the oscillators is now over, and a backlog of behavior data has been accumulated, further investigation should produce more positive results. A repetition of the tests described in Section 3 would be in order, as would be further testing with the Sulzer D5 oscillators mounted in shock mounts.

Test periods should be at least 48 hours in length and, if time permits, each test should be preceded and followed by a similar amount of time with the oscillators in a normal position. Recording equipment utilizing 100-division paper should be used to record the phase comparator output so that with ten micro-seconds full-scale deflection, phase shift at 100 kilocycles may be read to one-tenth or one-twentieth of a micro-second.

BIBLIOGRAPHY

1. Bell Telephone Laboratories, Inc. NAVSHIPS 91729, Instruction Book for RF OSCILLATOR 0-76A/U (Western Electric D-175730-62 Frequency Standard). [n.d.] Western Electric Company, Inc. New York, N. Y. Contract NObsr-57282, Bureau of Ships, Navy Department.
2. Blagoveshchensky, S. N. Theory of Ship Motion. 2 vols. Dover Publications, Inc., 1962.
3. Bowker, A. H. and G. J. Lieberman. Engineering Statistics. Prentice-Hall, Inc., 1959.
4. Harris, C. M. and C. E. Crede, editors. Shock and Vibration Handbook, Volume 2. McGraw-Hill, 1961.
5. Marine Technology Society, Washington, D. C. Buoy Technology, Transactions of the 1964 Buoy Technology Symposium, 24-25 March, 1964.
6. Sulzer Laboratories, Inc., 621 Lofstrand Lane, Rockville, Md. Instruction Manual for Model 2.5 Frequency Standard. [n. d.]
7. Sulzer Laboratories, Inc., 621 Lofstrand Lane, Rockville, Md. Instruction Manual for Model D5 Oscillator. [n. d.]
8. Todd, F. H. Ship Hull Vibration. Edward Arnold (Publishers) Ltd., London, 1961.
9. Wah, T., editor. A Guide for the Analysis of Ship Structures. U. S. Department of Commerce, 1960.

The first part of the book is devoted to the study of the properties of the function $f(x)$ defined by the equation $f(x) = \int_0^x \sin t dt$. It is shown that $f(x)$ is a continuous function and that it is differentiable at every point x where the integrand is continuous. The function $f(x)$ is called the sine integral and is denoted by $\text{Si}(x)$.

In the second part of the book, we study the properties of the function $f(x) = \int_0^x \cos t dt$. It is shown that $f(x)$ is a continuous function and that it is differentiable at every point x where the integrand is continuous. The function $f(x)$ is called the cosine integral and is denoted by $\text{Ci}(x)$.

The third part of the book is devoted to the study of the properties of the function $f(x) = \int_0^x \frac{\sin t}{t} dt$. It is shown that $f(x)$ is a continuous function and that it is differentiable at every point x where the integrand is continuous. The function $f(x)$ is called the sine integral and is denoted by $\text{Si}(x)$.

In the fourth part of the book, we study the properties of the function $f(x) = \int_0^x \frac{\cos t}{t} dt$. It is shown that $f(x)$ is a continuous function and that it is differentiable at every point x where the integrand is continuous. The function $f(x)$ is called the cosine integral and is denoted by $\text{Ci}(x)$.

The fifth part of the book is devoted to the study of the properties of the function $f(x) = \int_0^x \frac{\sin t}{t^2} dt$. It is shown that $f(x)$ is a continuous function and that it is differentiable at every point x where the integrand is continuous. The function $f(x)$ is called the sine integral and is denoted by $\text{Si}(x)$.

APPENDIX

A COMPUTER PROGRAM FOR FITTING A STRAIGHT LINE
TO DATA POINTS AND COMPUTING THE STANDARD DEVIATION
OF THE POINTS ABOUT THE FITTED LINE

THE UNIVERSITY OF CHICAGO
 LIBRARY
 540 EAST 57TH STREET
 CHICAGO, ILL. 60637

PROGRAM LINEFIT

THIS PROGRAM FINDS THE SLOPE AND Y-INTERCEPT OF THE BEST STRAIGHT LINE (IN THE LEAST SQUARES SENSE) FITTED TO A SET OF DATA POINTS. THE X DATA ARE ASSUMED TO BE WITHOUT ERROR. TRANSFORMATIONS TO EITHER OR BOTH VARIABLES CAN BE MADE. THE PROGRAM WILL ALSO COMPUTE THE STANDARD DEVIATION OF THE POINTS.

USAGE

1. CALLING SEQUENCE

MAIN PROGRAM. THE FOLLOWING DATA CARDS ARE READ.

A. FORMAT (3I4) - FIRST CARD

N, RIGHT-JUSTIFIED NUMBER OF DATA POINTS.

ICODEX, TRANSFORMATION CODES FOR X

ICODEY, TRANSFORMATION CODES FOR Y

B. FORMAT (12F6.0) - SUBSEQUENT CARDS.

X(1),Y(1),X(2),Y(2), ETC.

C. TRANSFORMATION CODES

=1 NONE

=2 VARIABLE REPLACED BY SQUARE ROOT OF VARIABLE

=3 VARIABLE REPLACED BY SQUARE OF VARIABLE

=4 VARIABLE REPLACED BY LOG TO BASE 10 OF VARIABLE

=5 VARIABLE REPLACED BY LOG TO BASE E OF VARIABLE

11111

TEST PERIOD FROM 1700 4 OCT TO 1300 7 OCT, S1, STATIC ONE, FINAL
DIMENSION X(200),XSAVE(200),Y(200),YSAVE(200),YFIT(200),DIFFS(200)

104 READ 999, N, ICODEX, ICODEY

999 FORMAT(3I4)

PRINT 998,N,ICODEX,ICODEY

998 FORMAT(4H1N =I4,3X8HICODEX =I2,3X8HICODEY =I2//)

READ 100, (X(I),Y(I),I=1,N)

100 FORMAT(12F6.0)

DO 996 I=1,N

XSAVE(I)=X(I)

996 YSAVE(I)=Y(I)

YSUM = 0.

SUMX = 0.

SUMY = 0.

SUMXY = 0.

SUMXX = 0.

CALL TRANS(N,X,Y,ICODEX,ICODEY)

XN = N

DO 30 I = 1, N

SUMX=SUMX+X(I)

SUMY = SUMY+Y(I)

SUMXX = SUMXX + (X(I)*X(I))

30 SUMXY=SUMXY+ (X(I)*Y(I))

DENOM = XN*SUMXX-SUMX*SUMX

ANUM = SUMY * SUMXX - SUMX * SUMXY

A = ANUM / DENOM

BNUM= XN*SUMXY-SUMX*SUMY

B = BNUM / DENOM

DO 40 J = 1,N

YC = A + B * X(J)

DIFF = Y(J) - YC

40 YSUM = YSUM + DIFF*DIFF

S2 = YSUM / (XN - 1.)

SIG=S2/DENOM

SRA=SQRTF(SUMXX*SIG)

SRB=SQRTF(XN*SIG)

PRINT 997, A, B, SRA, SRB

997 FORMAT(24H0 STRAIGHT LINE FITTING// 25H USING THE FORM Y=BX + A,
1/ 4H A = E14.8/ 4H B = E14.8/ 26H STANDARD DEVIATION OF A = E14.8



```

2/ 26H STANDARD DEVIATION OF B = E14.8)
SUMFIT=.0
SDIFFS=0.
SDIFFSQ=0.
DO 90 I=1,N
YFIT(I)=B*X(I)+A
DIFFS(I)=YFIT(I)-Y(I)
SDIFFS=SDIFFS+DIFFS(I)
SDIFFSQ=SDIFFSQ+DIFFS(I)**2
90 SUMFIT=SUMFIT+ DIFFS(I)
995 PRINT 99,SUMFIT,(X(I),YSAVE(I),Y(I),YFIT(I),DIFFS(I),I=1,N)
99 FORMAT(9H0SUMFIT =E12.5///10X1HX14X1HY9X10HYTRANSP0SE8X4HYFIT11X5
1DIFFS///(5E15.5)).
SIGMA=SQRTF((SDIFFSQ-SDIFFS**2/XN)/(XN -1.))
PRINT 1000,SIGMA
1000 FORMAT (1H0,7HSIGMA =E15.8)
GO TO 104
106 STOP
END
SUBROUTINE TRANS(N, X, Y, ICODEX, ICODEY)
DIMENSION X(200), Y(200)
GO TO ( 10, 20, 30, 40, 50), ICODEX
20 DO 21 I = 1,N
21 X(I)=SQRTF(ABSF(X(I)))
GO TO 10
30 DO 31 I = 1,N
31 X(I) = X(I) * X(I)
GO TO 10
40 DO 41 I = 1,N
41 X(I)=LOG10F(X(I))
GO TO 10
50 DO 51 I = 1,N
51 X(I)=LOGF(X(I))
10 GO TO (100, 200, 300, 400, 500), ICODEY
200 DO 201 I = 1,N
201 Y(I)=SQRTF(ABSF(Y(I)))
100 RETURN
300 DO 301 I = 1,N
301 Y(I) = Y(I) * Y(I)
RETURN
400 DO 401 I = 1,N
401 Y(I)=LOG10F(Y(I))
RETURN
500 DO 501 I = 1,N
501 Y(I)=LOGF(Y(I))
END
END

```


N = 68 ICODEX = 1 ICODEY = 1

STRAIGHT LINE FITTING

USING THE FORM $Y=BX + A$,

A = -.90372827E+03

B = -.23075352E+01

STANDARD DEVIATION OF A = .13877674E+01

STANDARD DEVIATION OF B = .34962902E-01

SUMFIT = .10431E-06

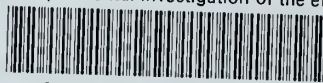
X	Y	YTRANPOSE	YFIT	DIFFS
.10000E+01	-.90400E+03	-.90400E+03	-.90604E+03	-.20358E+01
.20000E+01	-.91700E+03	-.91700E+03	-.90834E+03	.86567E+01
.30000E+01	-.91000E+03	-.91000E+03	-.91065E+03	-.65088E+00
.40000E+01	-.91000E+03	-.91000E+03	-.91296E+03	-.29584E+01
.50000E+01	-.92400E+03	-.92400E+03	-.91527E+03	.87341E+01
.60000E+01	-.91700E+03	-.91700E+03	-.91757E+03	-.57348E+00
.70000E+01	-.91000E+03	-.91000E+03	-.91988E+03	-.98810E+01
.80000E+01	-.93100E+03	-.93100E+03	-.92219E+03	.88114E+01
.90000E+01	-.93100E+03	-.93100E+03	-.92450E+03	.65039E+01
.10000E+02	-.93100E+03	-.93100E+03	-.92680E+03	.41964E+01
.11000E+02	-.93100E+03	-.93100E+03	-.92911E+03	.18888E+01
.12000E+02	-.93100E+03	-.93100E+03	-.93142E+03	-.41869E+00
.13000E+02	-.93100E+03	-.93100E+03	-.93373E+03	-.27262E+01
.14000E+02	-.93100E+03	-.93100E+03	-.93603E+03	-.50338E+01
.15000E+02	-.93800E+03	-.93800E+03	-.93834E+03	-.34130E+00
.16000E+02	-.94400E+03	-.94400E+03	-.94065E+03	.33512E+01
.17000E+02	-.94400E+03	-.94400E+03	-.94296E+03	.10436E+01
.18000E+02	-.94400E+03	-.94400E+03	-.94526E+03	-.12639E+01
.19000E+02	-.94400E+03	-.94400E+03	-.94757E+03	-.35714E+01
.20000E+02	-.94400E+03	-.94400E+03	-.94988E+03	-.58790E+01
.21000E+02	-.95800E+03	-.95800E+03	-.95219E+03	.58135E+01
.22000E+02	-.96500E+03	-.96500E+03	-.95449E+03	.10506E+02
.23000E+02	-.96500E+03	-.96500E+03	-.95680E+03	.81984E+01
.24000E+02	-.95800E+03	-.95800E+03	-.95911E+03	-.11091E+01
.25000E+02	-.96500E+03	-.96500E+03	-.96142E+03	.35833E+01
.26000E+02	-.95800E+03	-.95800E+03	-.96372E+03	-.57242E+01
.27000E+02	-.96500E+03	-.96500E+03	-.96603E+03	-.10317E+01
.28000E+02	-.96500E+03	-.96500E+03	-.96834E+03	-.33393E+01
.29000E+02	-.97200E+03	-.97200E+03	-.97065E+03	.13532E+01
.30000E+02	-.96500E+03	-.96500E+03	-.97295E+03	-.79543E+01
.31000E+02	-.97900E+03	-.97900E+03	-.97526E+03	.37381E+01
.32000E+02	-.97200E+03	-.97200E+03	-.97757E+03	-.55694E+01
.33000E+02	-.97900E+03	-.97900E+03	-.97988E+03	-.87693E+00
.34000E+02	-.96500E+03	-.96500E+03	-.98218E+03	-.17184E+02
.35000E+02	-.97900E+03	-.97900E+03	-.98449E+03	-.54920E+01
.36000E+02	-.99300E+03	-.99300E+03	-.98680E+03	.62005E+01
.37000E+02	-.98600E+03	-.98600E+03	-.98911E+03	-.31071E+01
.38000E+02	-.99300E+03	-.99300E+03	-.99141E+03	.15854E+01
.39000E+02	-.98600E+03	-.98600E+03	-.99372E+03	-.77221E+01
.40000E+02	-.99300E+03	-.99300E+03	-.99603E+03	-.30297E+01
.41000E+02	-.99300E+03	-.99300E+03	-.99834E+03	-.53372E+01
.42000E+02	-.99300E+03	-.99300E+03	-.10006E+04	-.76447E+01

.43000E+02	-.10000E+04	-.10000E+04	-.10030E+04	-.29523E+01
.44000E+02	-.10000E+04	-.10000E+04	-.10053E+04	-.52598E+01
.45000E+02	-.10070E+04	-.10070E+04	-.10076E+04	-.56736E+00
.46000E+02	-.10140E+04	-.10140E+04	-.10099E+04	.41251E+01
.47000E+02	-.10070E+04	-.10070E+04	-.10122E+04	-.51824E+01
.48000E+02	-.10140E+04	-.10140E+04	-.10145E+04	-.48996E+00
.49000E+02	-.10280E+04	-.10280E+04	-.10168E+04	.11203E+02
.50000E+02	-.10280E+04	-.10280E+04	-.10191E+04	.88950E+01
.51000E+02	-.10210E+04	-.10210E+04	-.10214E+04	-.41257E+00
.52000E+02	-.10280E+04	-.10280E+04	-.10237E+04	.42799E+01
.53000E+02	-.10210E+04	-.10210E+04	-.10260E+04	-.50276E+01
.54000E+02	-.10210E+04	-.10210E+04	-.10283E+04	-.73352E+01
.55000E+02	-.10350E+04	-.10350E+04	-.10306E+04	.43573E+01
.56000E+02	-.10350E+04	-.10350E+04	-.10330E+04	.20498E+01
.57000E+02	-.10420E+04	-.10420E+04	-.10353E+04	.67422E+01
.58000E+02	-.10420E+04	-.10420E+04	-.10376E+04	.44347E+01
.59000E+02	-.10420E+04	-.10420E+04	-.10399E+04	.21272E+01
.60000E+02	-.10420E+04	-.10420E+04	-.10422E+04	-.18038E+00
.61000E+02	-.10420E+04	-.10420E+04	-.10445E+04	-.24879E+01
.62000E+02	-.10420E+04	-.10420E+04	-.10468E+04	-.47955E+01
.63000E+02	-.10420E+04	-.10420E+04	-.10491E+04	-.71030E+01
.64000E+02	-.10490E+04	-.10490E+04	-.10514E+04	-.24105E+01
.65000E+02	-.10560E+04	-.10560E+04	-.10537E+04	.22819E+01
.66000E+02	-.10630E+04	-.10630E+04	-.10560E+04	.69744E+01
.67000E+02	-.10690E+04	-.10690E+04	-.10583E+04	.10667E+02
.68000E+02	-.10630E+04	-.10630E+04	-.10606E+04	.23593E+01

SIGMA = .56589160E+01

thesA965

An experimental investigation of the eff



3 2768 001 91068 0

DUDLEY KNOX LIBRARY